

احجز مكانك واستعد للامتحان بثقة كاملة

$$F = \frac{Gm_1m_2}{r^2}$$

ملزمة الفيزياء الفصل الثالث

12 Inspire متقدم لعام 2026

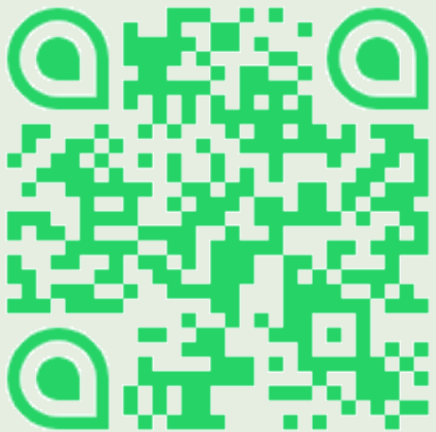
$$\Sigma F = ma$$

$$\Sigma F$$

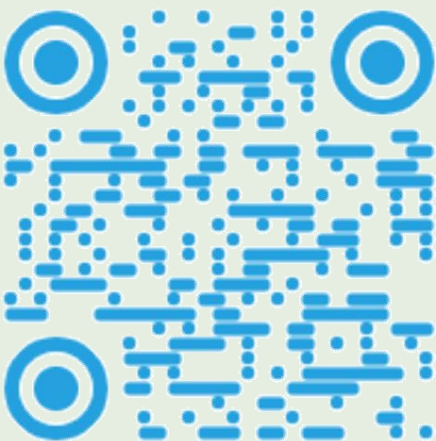
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شرح لدروس الفصل
الثالث كامل

ب199
درهم فقط

ملازم

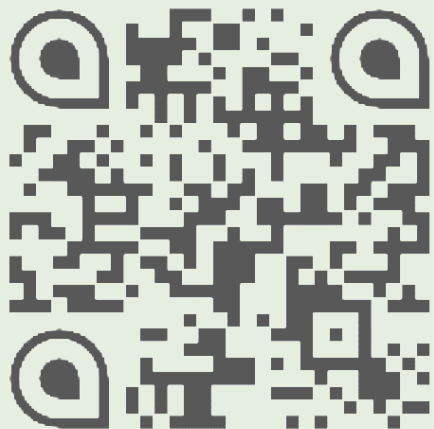
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Module (22): Quantum Theory and the Atom

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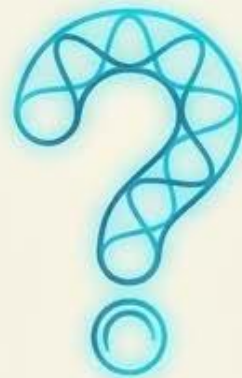
Module (22): Quantum Theory and the Atom

01

First Lesson:
A Particle Model of Waves

A Particle Model of Waves

From Classical Wave Theory to Quantum Realities.



Expectation vs. Reality		
The Established Rule	Phenomenon 1 (Failure)	Phenomenon 2 (Failure)
James Maxwell's electromagnetic wave theory successfully models light as continuous changing electric and magnetic fields. It perfectly explains: - Interference - Diffraction - Polarization	Emission Spectra. Fails to explain the spectrum of electromagnetic waves emitted by hot objects.	The Photoelectric Effect. Fails to explain the emission of electrons from metals exposed to ultraviolet radiation.

Mr. Mohamad's Insight:
 To solve these two mysteries, physics had to completely reimagine light—not just as a continuous wave, but as individual packets of energy.



Lower Temperature
(Deep Red)



Medium Temperature
(Bright Yellow/Orange)



Higher Temperature
(White/Blue)

Phenomenon 1: Incandescence

Definition:

The emission of light from a hot object.

The Mechanism:

As potential difference increases, the filament's temperature rises.

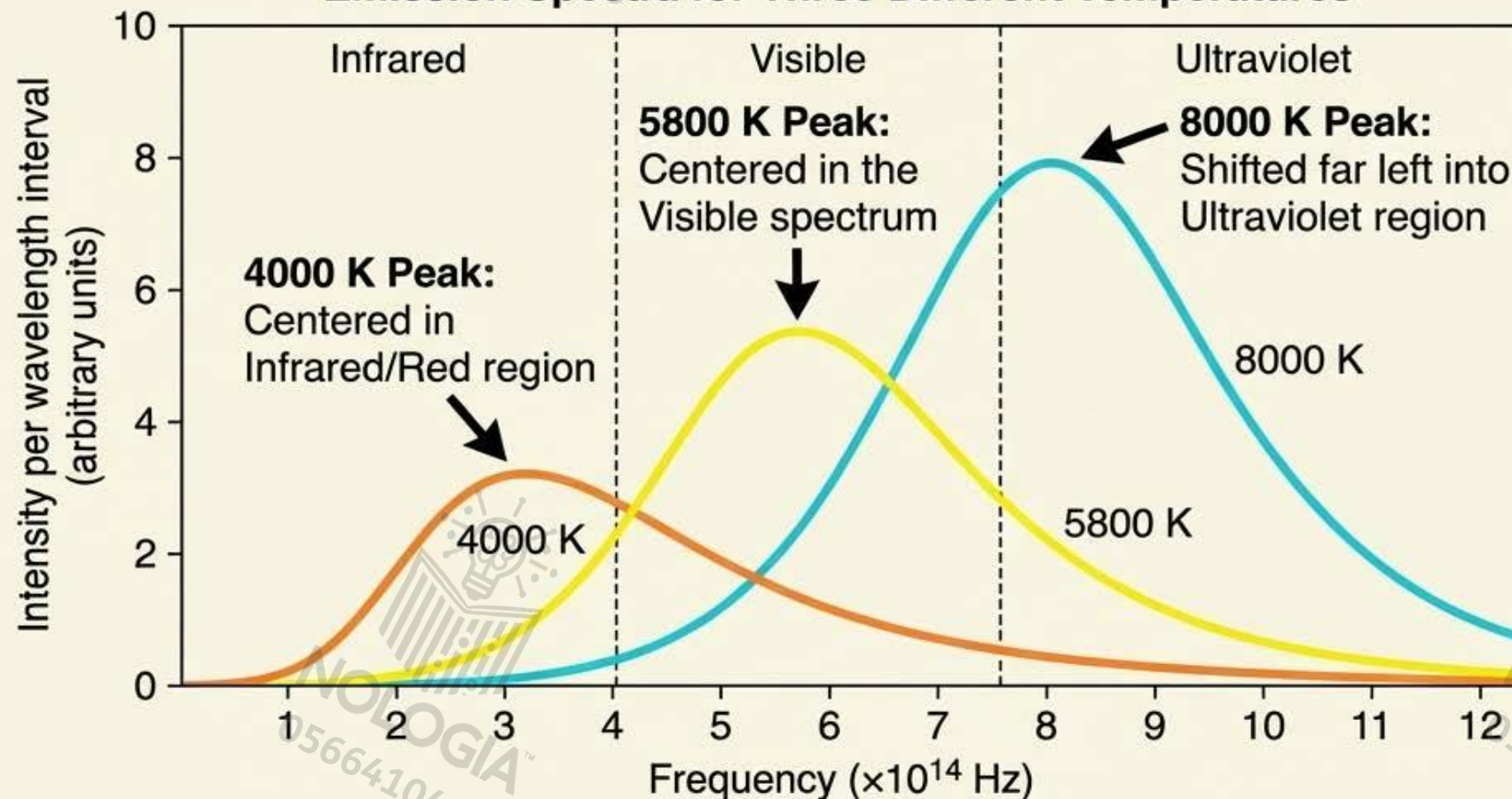
The Observation:

The emitted color explicitly shifts from lower-frequency (red) to higher-frequency (blue and violet) as the object gets hotter.

Deconstructing Emission Spectra

An **emission spectrum** is a graph of the intensity of radiation emitted from an object over a range of frequencies.

Emission Spectra for Three Different Temperatures



Rule Box

Rule 1:
Higher Temperature = Greater total energy emitted (larger area under the curve).

Rule 2:
Higher Temperature = Higher peak frequency (peak shifts right toward UV).

The Astronomy Connection

$$P \propto T^4$$

The total power emitted by an object is proportional to its Kelvin temperature raised to the fourth power.

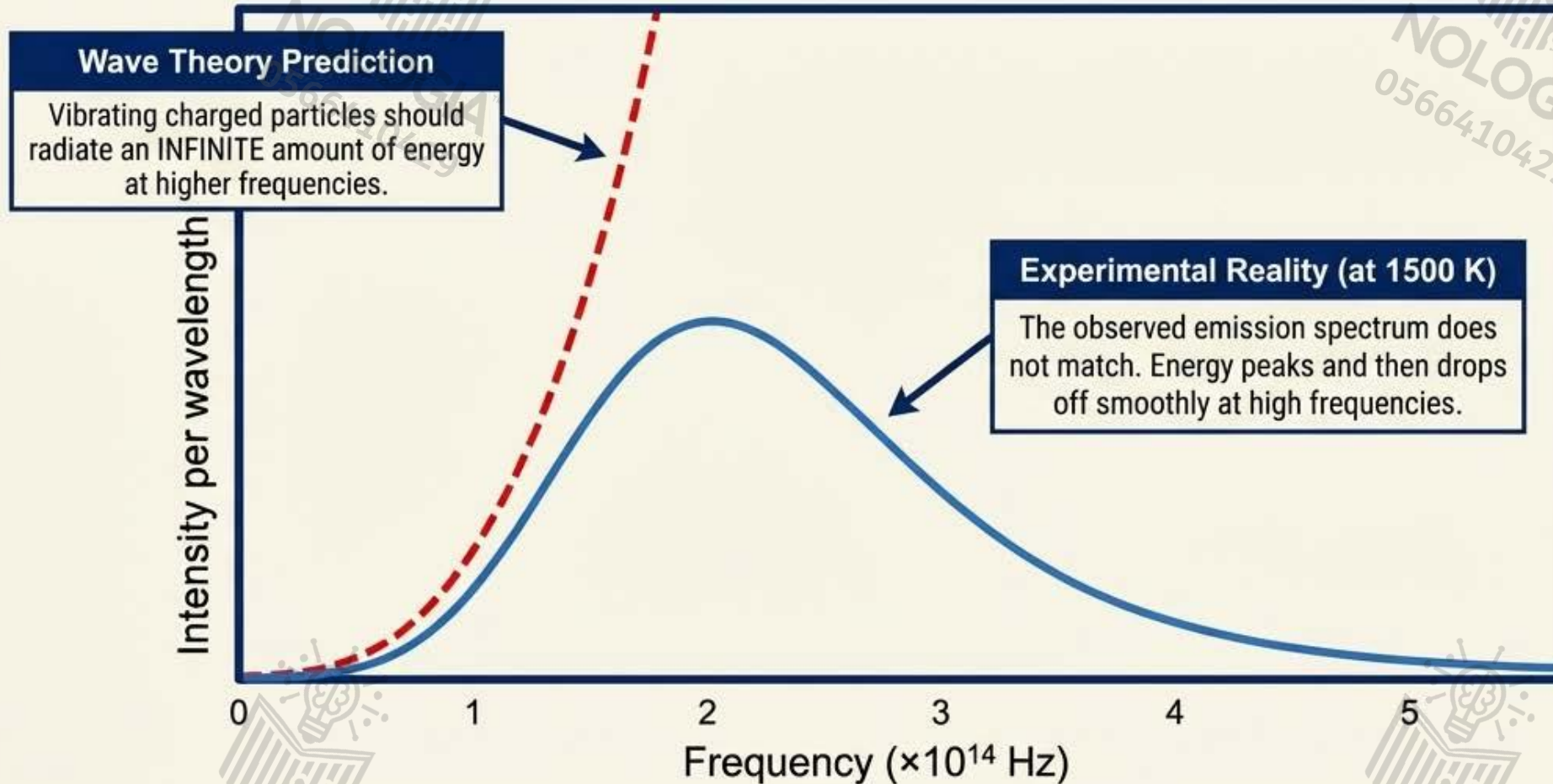
Application Data (The Sun):

- Surface Temperature: ≈ 5800 K
- Total Radiated Power: 4×10^{26} W

Real-World Impact & Mr. Mohamad's Note

Because of the T^4 multiplier, the Sun radiates an enormous amount of energy. On average, every square meter of Earth's surface receives ≈ 1000 W from the Sun. That is enough energy hitting a **single square meter to power ten 100-W lightbulbs simultaneously!**

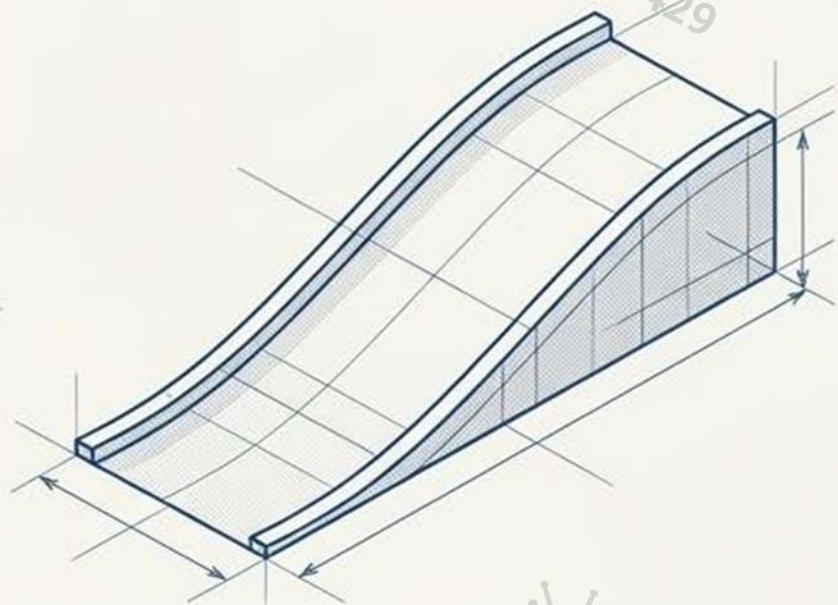
The Breakdown of Wave Theory



Verdict: Classical wave theory is fundamentally broken when predicting emission spectra. (The Ultraviolet Catastrophe)

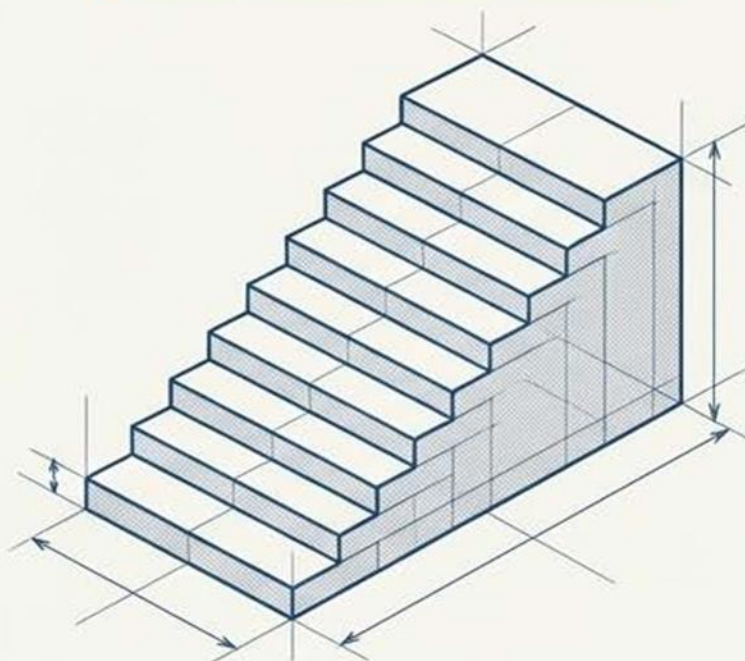
Planck's Quantum Leap (1900)

Classical Continuous Energy



Energy can be any value
(like sliding anywhere on a ramp).

Quantum Discrete Energy



Atoms can only emit/absorb energy in
specific, discrete bundles called quanta
(like resting only on specific stairs).

Formula Focus

$$E = nhf$$

E = Energy

n = Integer (0, 1, 2, 3...)

h = Planck's Constant
(6.626×10^{-34} J/Hz)

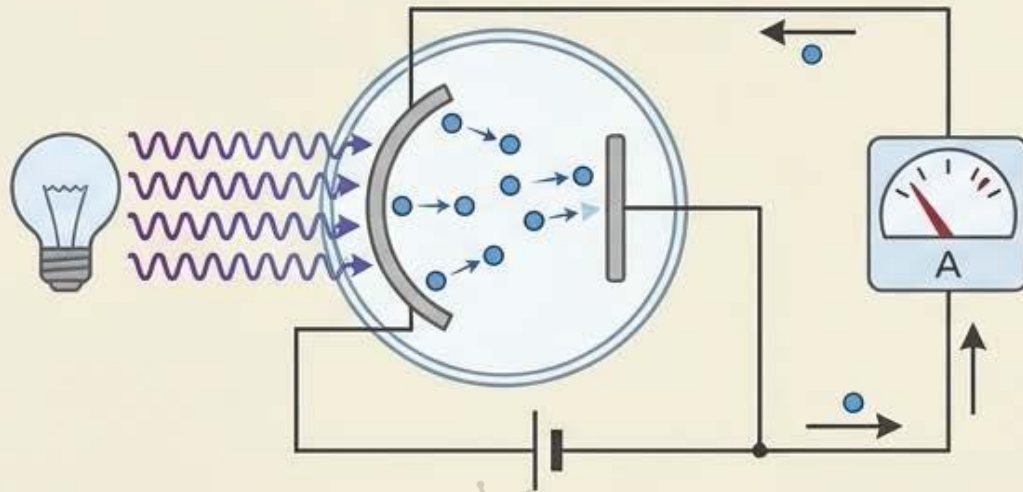
f = Frequency of vibration

Key Concept: Energy is quantized. An atom's energy changes only in multiples of hf , never fractions.

Phenomenon 2: The Photoelectric Effect

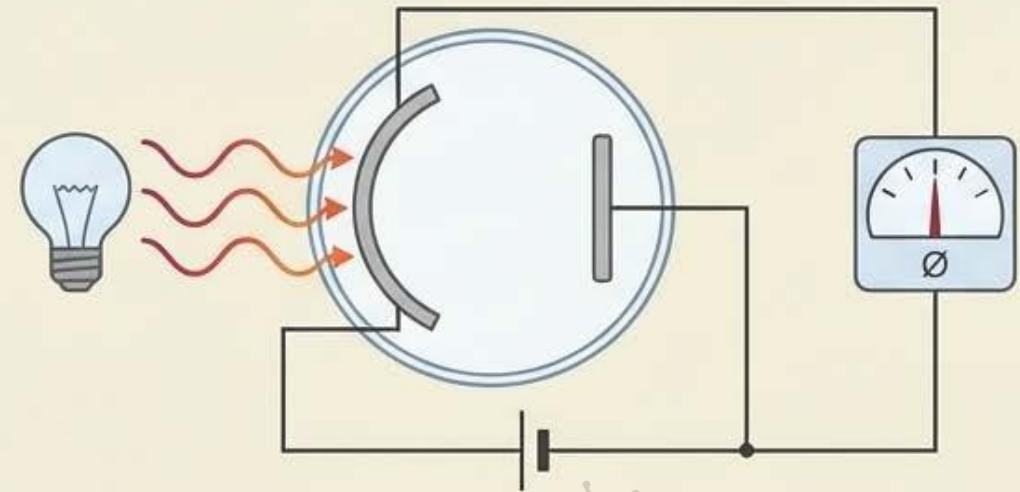
The **emission** of **electrons** when **electromagnetic radiation** falls on an object.

Ultraviolet Light (High Frequency)



Immediate electron ejection,
discharging the plate.

Visible Light (Lower Frequency)

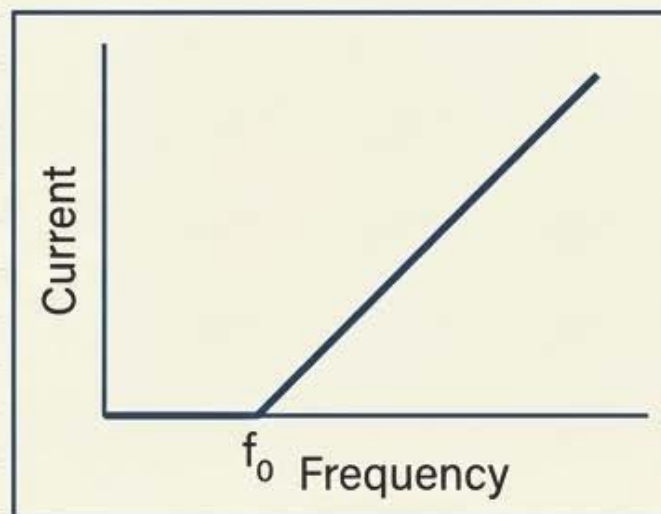


Even at extremely high intensity, exactly
zero electrons are ejected.

The Mystery: Classical wave theory predicted that a high-intensity wave should eventually build up enough energy to eject electrons, regardless of frequency. The experiment proved this completely wrong.

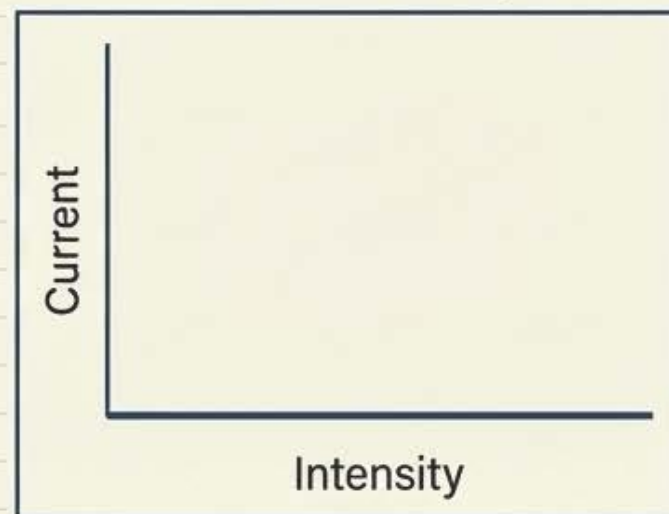
Analyzing the Photoelectric Data

Current vs. Frequency
(Constant Intensity)



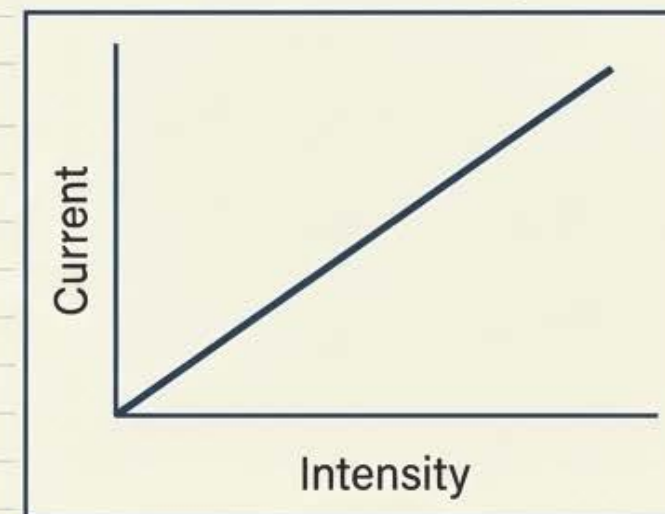
Threshold Frequency (f_0).
Electrons are only ejected if incident radiation exceeds a specific minimum frequency.

Current vs. Intensity
(Frequency $< f_0$)



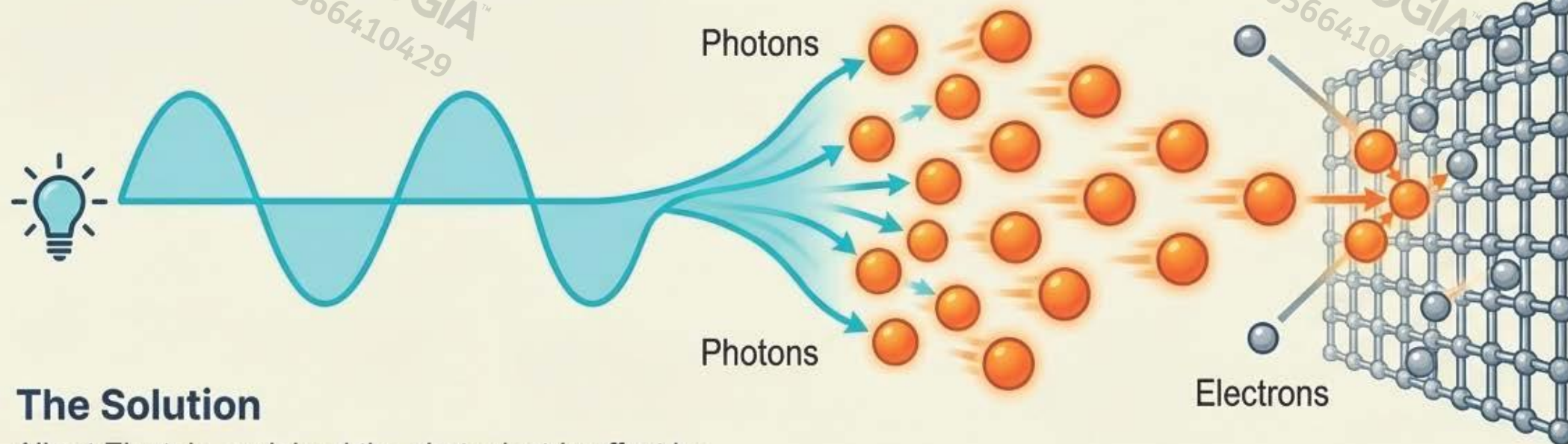
Insight:
Below f_0 , increasing light intensity does absolutely nothing. Current remains zero.

Current vs. Intensity
(Frequency $\geq f_0$)



Insight:
At or above f_0 , increasing intensity increases the NUMBER of electrons ejected (higher current).

Einstein's Photon (1905)



The Solution

Albert Einstein explained the photoelectric effect by proposing that light itself consists of discrete, quantized bundles of energy called Photons.

Energy of a Photon

$$E = hf$$

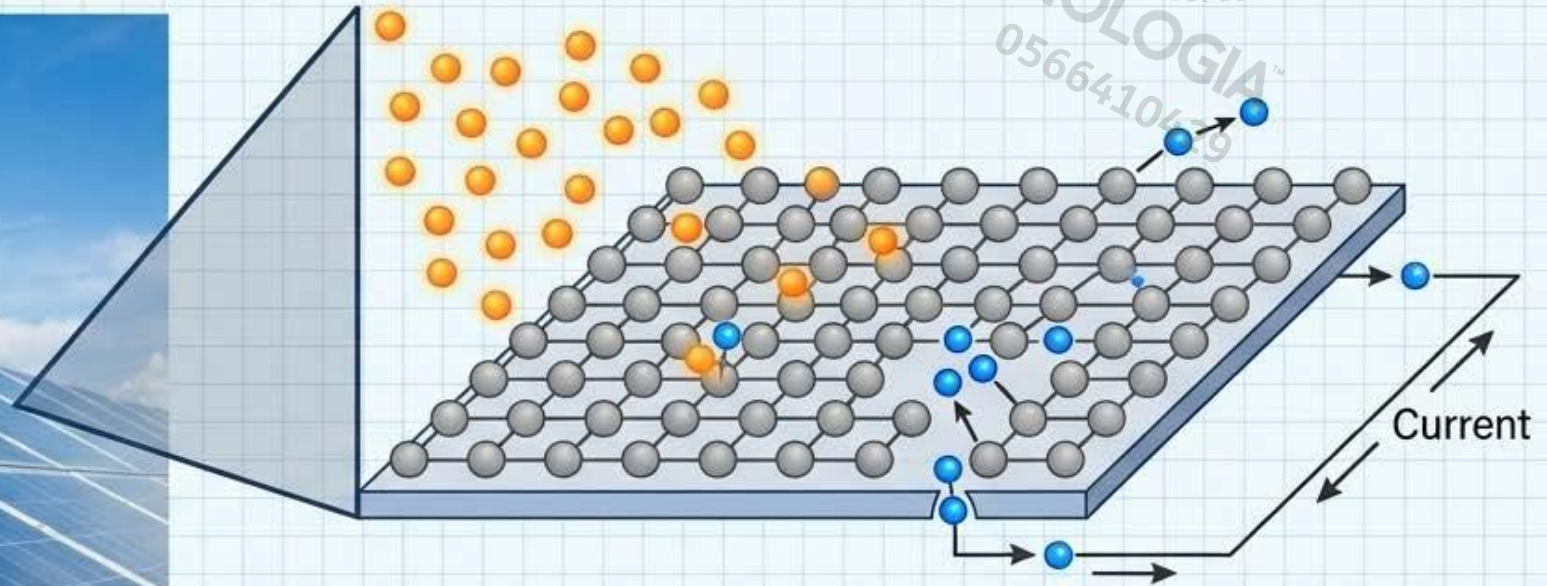
The energy of a single photon depends ONLY on its frequency.

The 1-to-1 Rule

One photon interacts with exactly one electron. If the photon's frequency (f) is below the threshold (f_0), its energy (hf) is too low to knock the electron loose. A million low-energy photons won't free a single electron.

Real-World Physics: Solar Panels

Application: Photovoltaic materials in solar cells.



1. Capture: Photons from the Sun strike the semiconducting material.

2. Absorption: If the photon's frequency exceeds the threshold frequency of the semiconductor, its energy is absorbed.

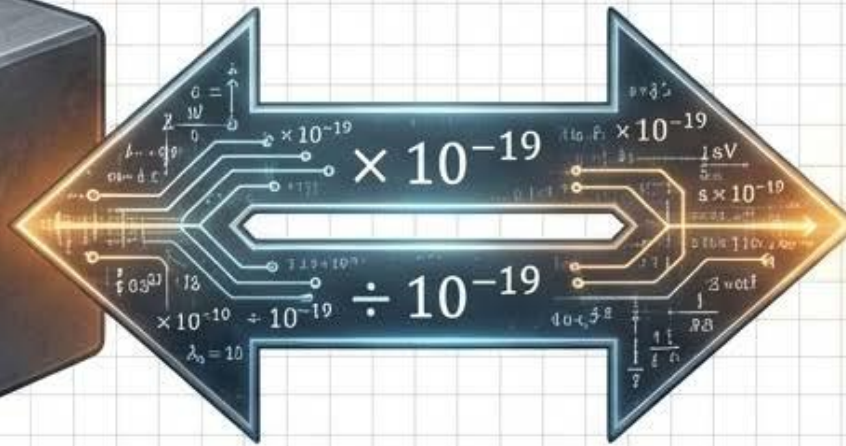
3. Emission: Electrons break free from their atoms.

4. Current: This flow of escaping photoelectrons is directed to form a usable electric current.

The Math: Mastering Electron Volts (eV)



Joules (J)



Electron Volts (eV)

The Problem: The Joule (J) is far too massive a unit for atomic-sized energy systems.

The Solution: The Electron Volt (eV).

- **Definition:** The energy of one single electron accelerated across a 1 V potential difference.

The Critical Conversion:

$$1 \text{ eV} = (1.602 \times 10^{-19} \text{ C})(1 \text{ V})$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

The Problem-Solving Blueprint

Step 1: Ensure your desired energy output is in electron volts (eV).

Step 2: Ensure your wavelength (λ) is converted to nanometers (nm).

The Ultimate Shortcut Formula

$$E = (1240 \text{ eV} \cdot \text{nm}) / \lambda$$

Step 3: Simply divide 1240 by λ to get the Energy.

Why this works:

$E = hf$, and $f = c/\lambda$. Therefore $E = hc/\lambda$. Because h and c are constants, converting their product (hc) into $\text{eV} \cdot \text{nm}$ yields exactly 1240. This bypasses complex scientific notation and super energy normolt. This bypasses complex scientific notation and saves critical minutes on exams!

Synthesis Matrix: Wave vs. Particle

Both models are required to completely describe light.

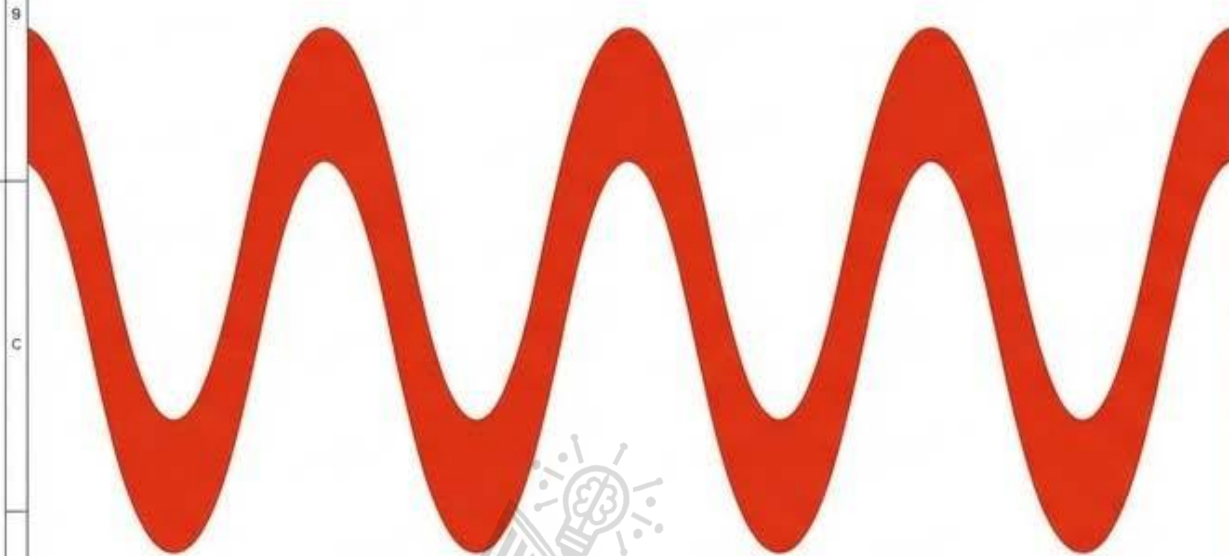
Physical Feature	Classical Wave Model	Quantum Particle Model
Nature of Energy	Continuous flow.	Quantized (discrete bundles).
Emission Spectra at High Temps	Fails (Predicts infinite energy).	Succeeds ($E=nhf$ perfectly matches observed peak).
Ejecting Electrons (Photoelectric)	Fails (Assumes high intensity is enough).	Succeeds (Requires minimum threshold frequency, $E=hf$).
Propagation (Interference/Diffraction)	Succeeds beautifully.	Cannot explain.

The Quantum Leap: From Continuous Waves to Discrete Packets

Einstein expanded on Planck's work, proving that light doesn't just behave as a continuous wave, but as distinct particles of energy called photons. A photon's energy is entirely dependent on its frequency: $E = hf$.

Classical View

Quantum View



Classical Theory: Energy builds up smoothly over time.

Einstein's Theory: Energy arrives in indivisible, discrete packets.

Scenario A

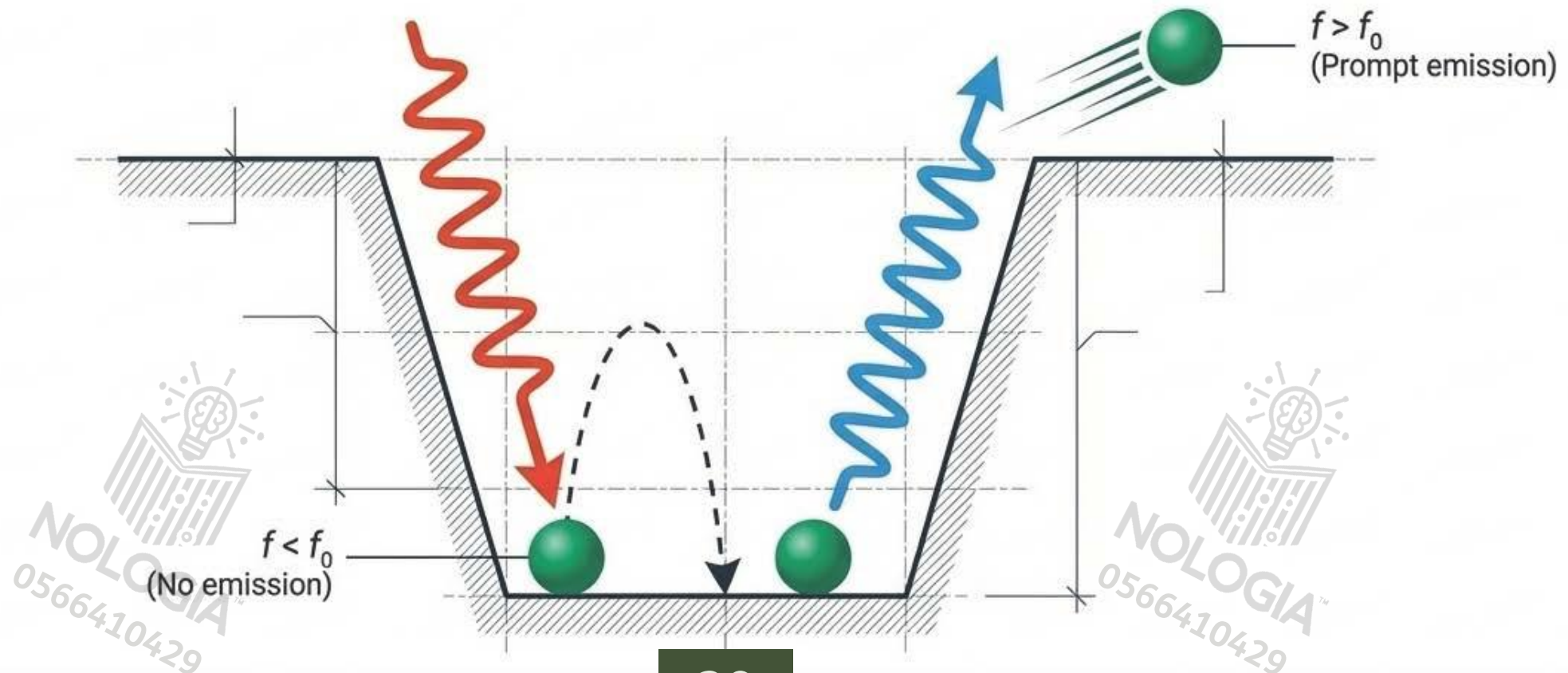
$f < f_0$ (No emission)
 

Scenario B

$f > f_0$ (Prompt emission)
 

Concept: The Mechanics of the Photoelectric Effect

Because one photon interacts with exactly one electron, low-frequency photons cannot "team up" to free an electron. The photon must possess a minimum threshold frequency (f_0) to provide the necessary energy to break the electron free.



Equation Anatomy: Kinetic Energy & The Work Function

$$KE = hf - hf_0$$

Incident Photon Energy (E).
The total energy delivered by the light.

Maximum Kinetic Energy
of the ejected electron.

The Work Function (W).
The exact energy "toll" required
to free the most loosely bound
electron from the metal.

Mr. Mohamad's Tip:

Remember your units!
Energy can be calculated
in Joules (J) or
electron-volts (eV).

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

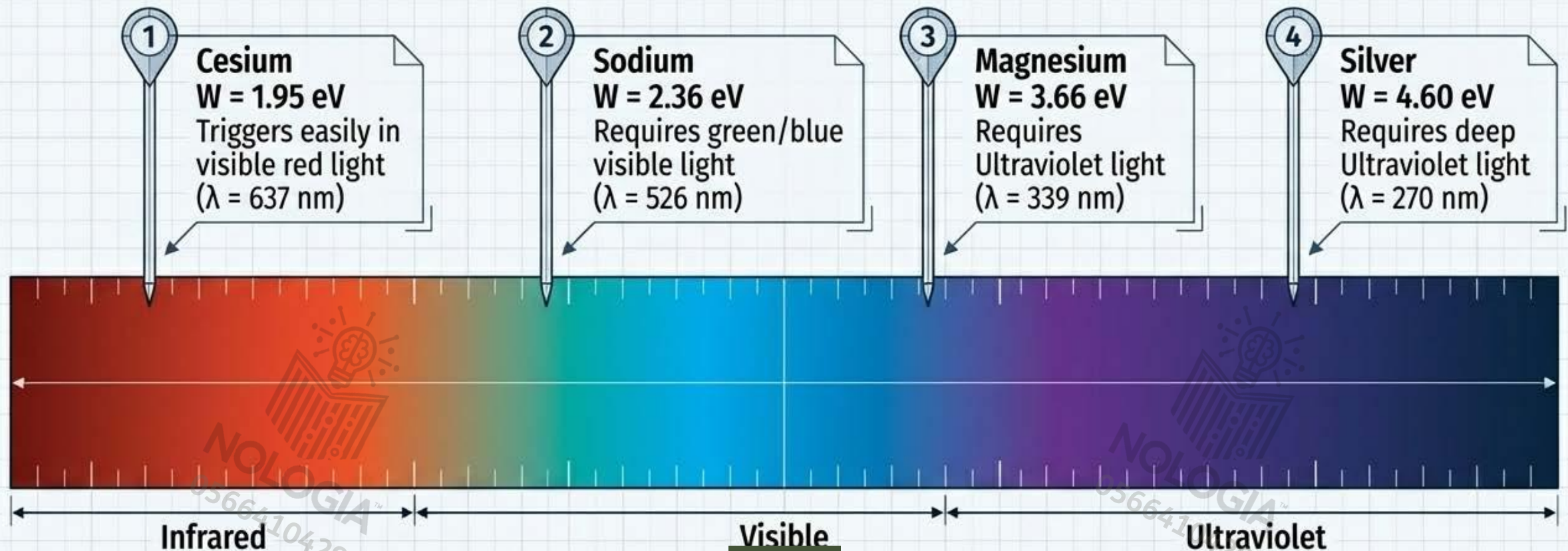
Mastery Example 1: Calculating Work Function & Kinetic Energy

A particular photocell uses a sodium cathode with a threshold wavelength (λ_0) of 526 nm. Ultraviolet radiation ($\lambda = 348$ nm) falls on it. Find the work function and the maximum kinetic energy of ejected electrons in eV.

1. The Setup	2. Work Function (W)	3. Kinetic Energy (KE)
$\lambda_0 = 526$ nm $\lambda = 348$ nm Shortcut Constant: $hc = 1240$ eV·nm	$W = \frac{hc}{\lambda_0}$ $W = \frac{1240}{526}$ $W = 2.36$ eV	First find Total Energy (E): $E = \frac{hc}{\lambda} = \frac{1240}{348} = 3.56$ eV Then apply the main equation: $KE = E - W$ $KE = 3.56$ eV – 2.36 eV $KE = 1.20$ eV

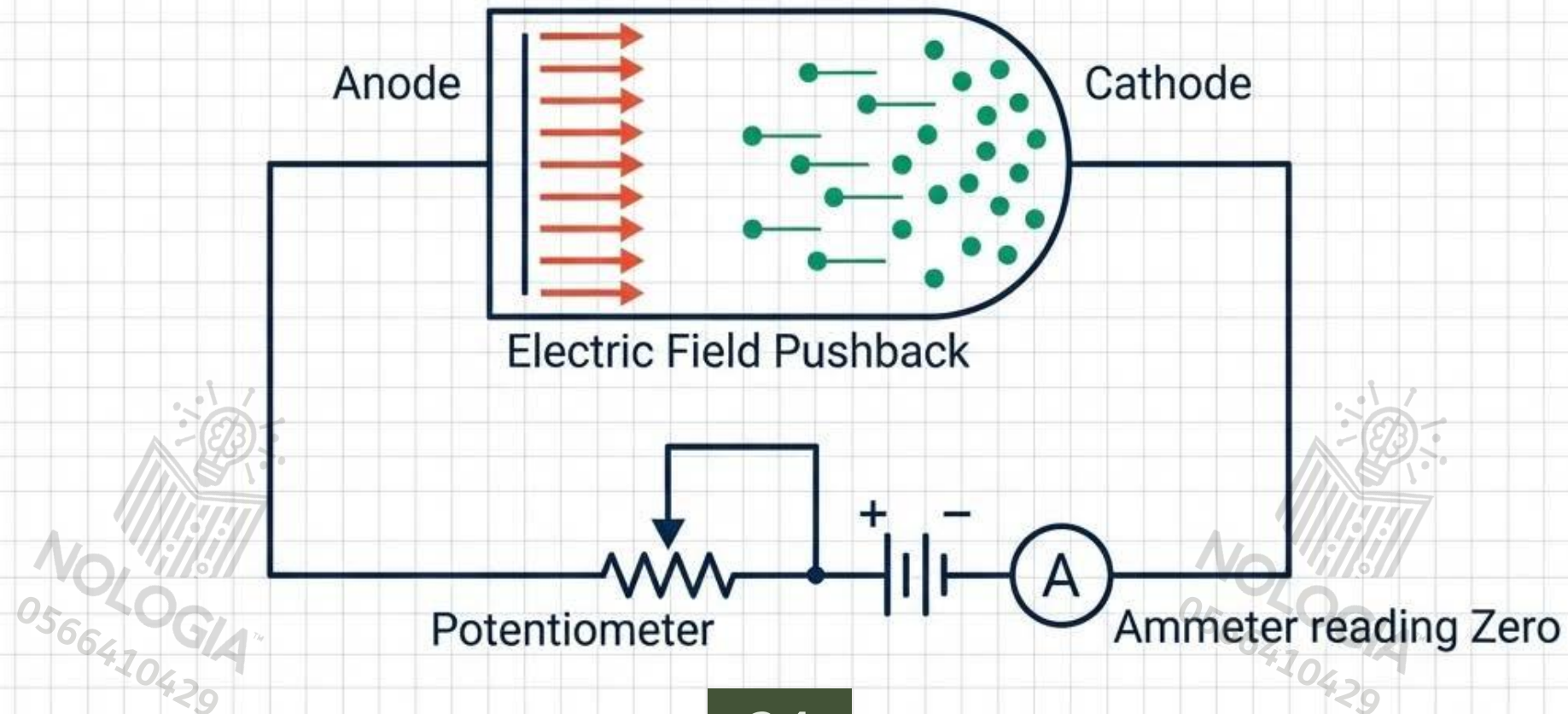
Material Matrix: Visualizing Thresholds Across Metals

Synthesis: The higher the Work Function, the deeper into the UV spectrum we must go to eject an electron.



Concept: Testing the Theory via Stopping Potential

How do we measure the kinetic energy of an electron we can't see? By forcing it to climb an electric "hill" until it stops completely.



Equation Anatomy: Stopping Potential

$$KE = -e\Delta V_0$$

Kinetic Energy of electrons as they leave the cathode.

Charge of an electron
(-1.602×10^{-19} C).

The Stopping Potential (Volts).
The precise negative voltage applied to the anode required to stop the current.

Key Insight: At the stopping potential, the maximum kinetic energy of the electrons perfectly equals the work done by the electric field to stop them. Multiplying the two negative values (charge and voltage) yields a positive Kinetic Energy.

Mastery Example 2: The Stopping Potential Math

The stopping potential difference of a photocell is 4.0 V. How much kinetic energy does the incident light give the electrons in both Joules and electron-volts?

1. Solve in Joules

Negatives cancel

$$KE = -(-1.602 \times 10^{-19} \text{ C})(-4.0 \text{ V})$$

$$KE = +6.4 \times 10^{-19} \text{ J}$$

Convert to eV

Divide by
 $1.602 \times 10^{-19} \text{ J/eV}$

2. Convert to electron-volts

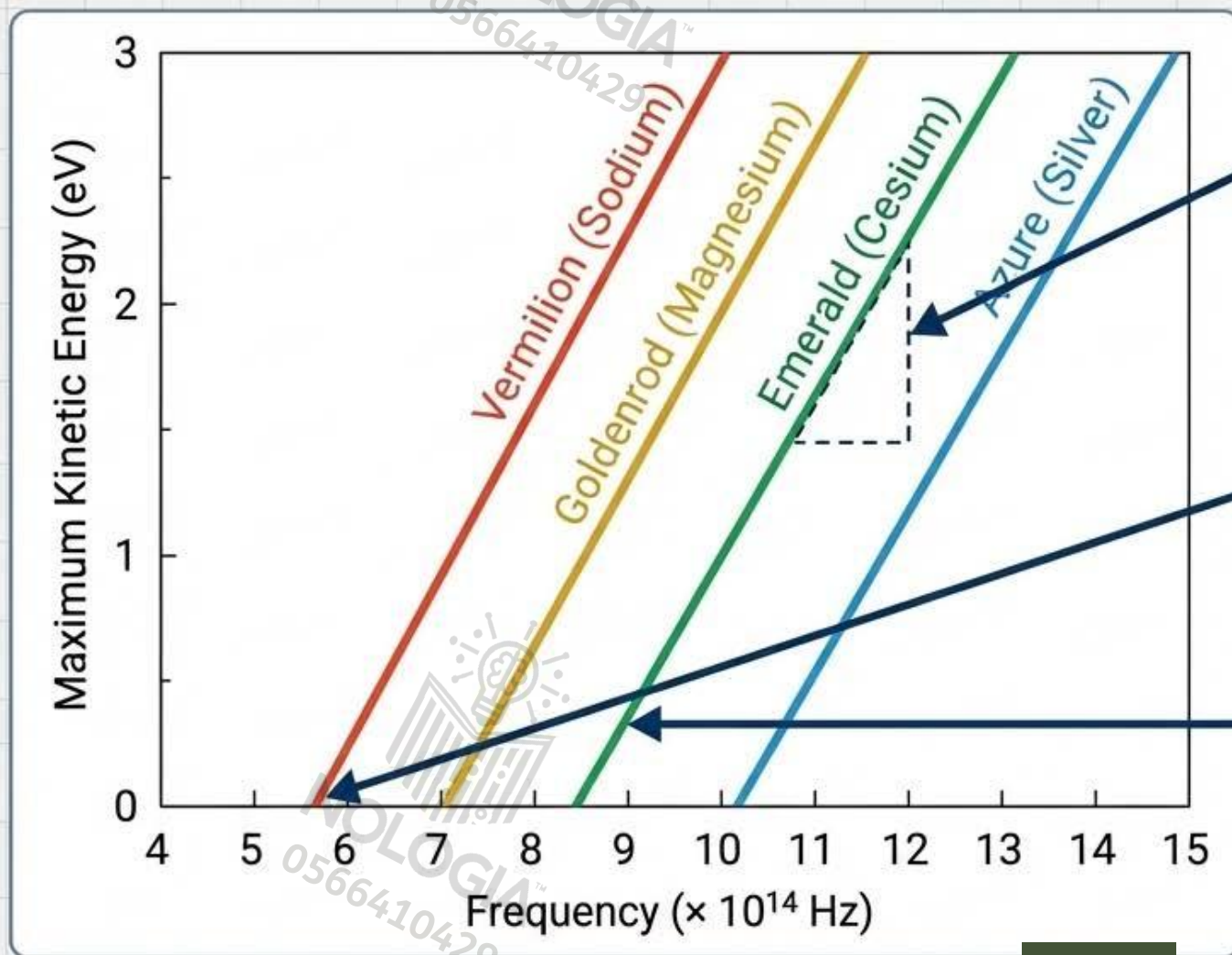
$$KE = \frac{6.4 \times 10^{-19} \text{ J}}{1.602 \times 10^{-19} \text{ J/eV}}$$

$$KE = 4.0 \text{ eV}$$

Mr. Mohamad's Exam Trick:

An electron stopped by a potential difference of 4 V always has a kinetic energy of exactly 4 eV. The numbers match!

Graph Deconstruction: Maximum KE vs. Frequency



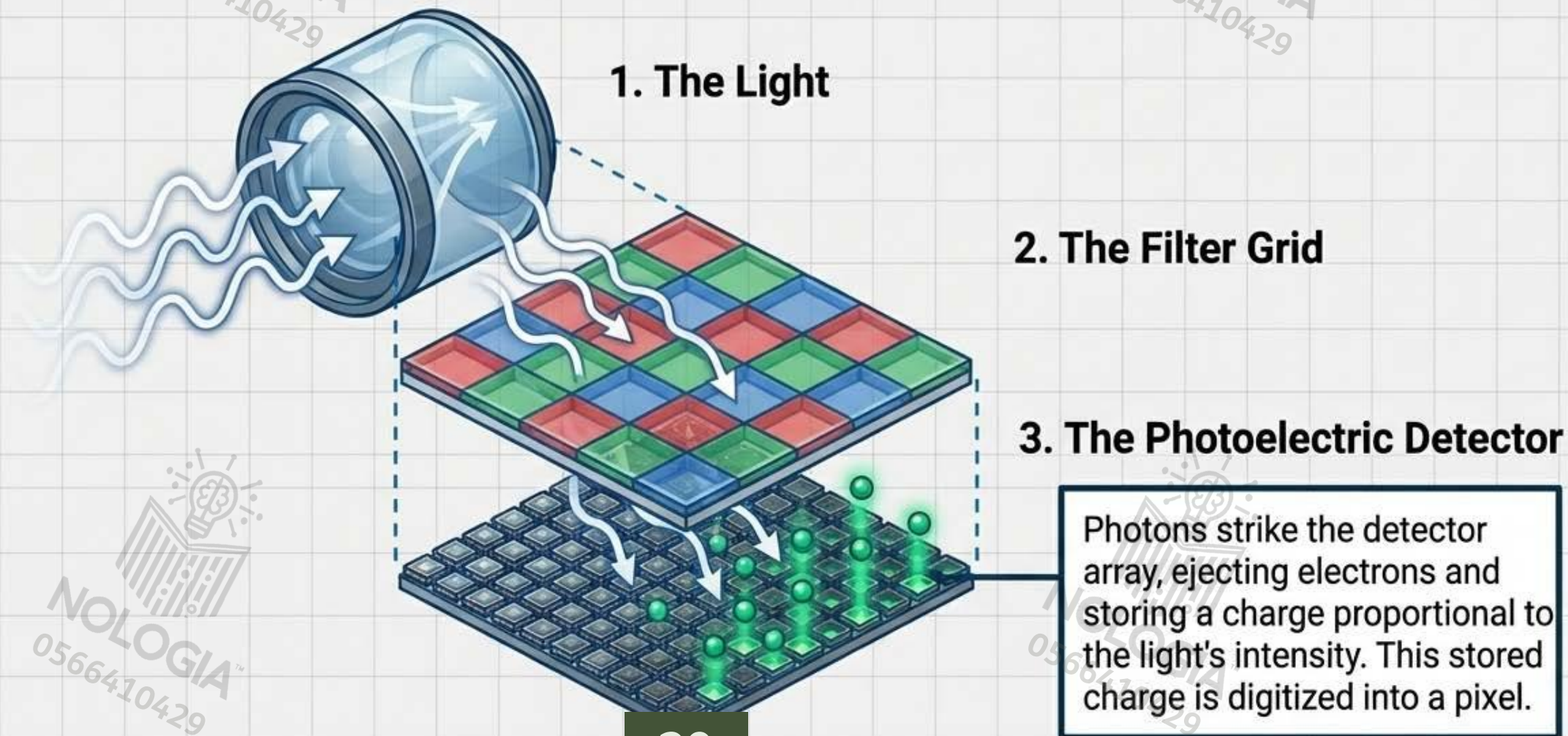
1. The Slope: The slope is universal. For every single metal, the slope is exactly Planck's constant ($h = 4.14 \times 10^{-15}$ eV/Hz).

2. The X-Intercept: This is the Threshold Frequency (f_0). Below this specific point, $KE = 0$ and no electrons are emitted.

3. Parallel Lines: Different metals have different starting thresholds, but the underlying physics (the slope) remains identical.

Real-World Application: The Digital Camera Array

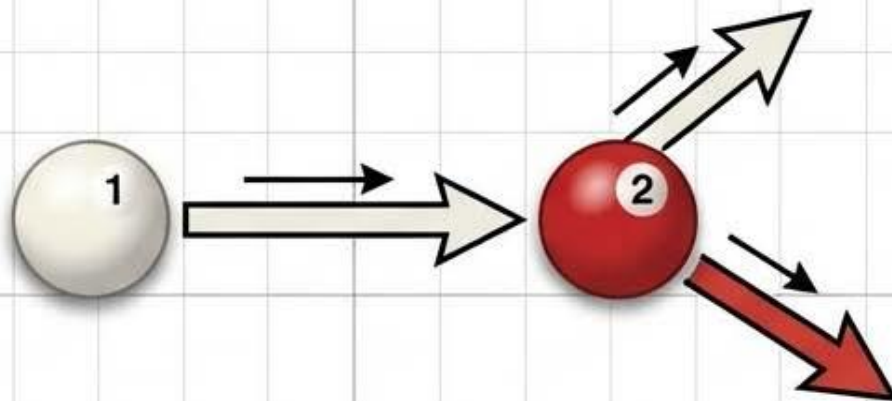
The exact same principle that ejects electrons from a metal cathode is used to capture photos in your smartphone via the **photovoltaic effect**.



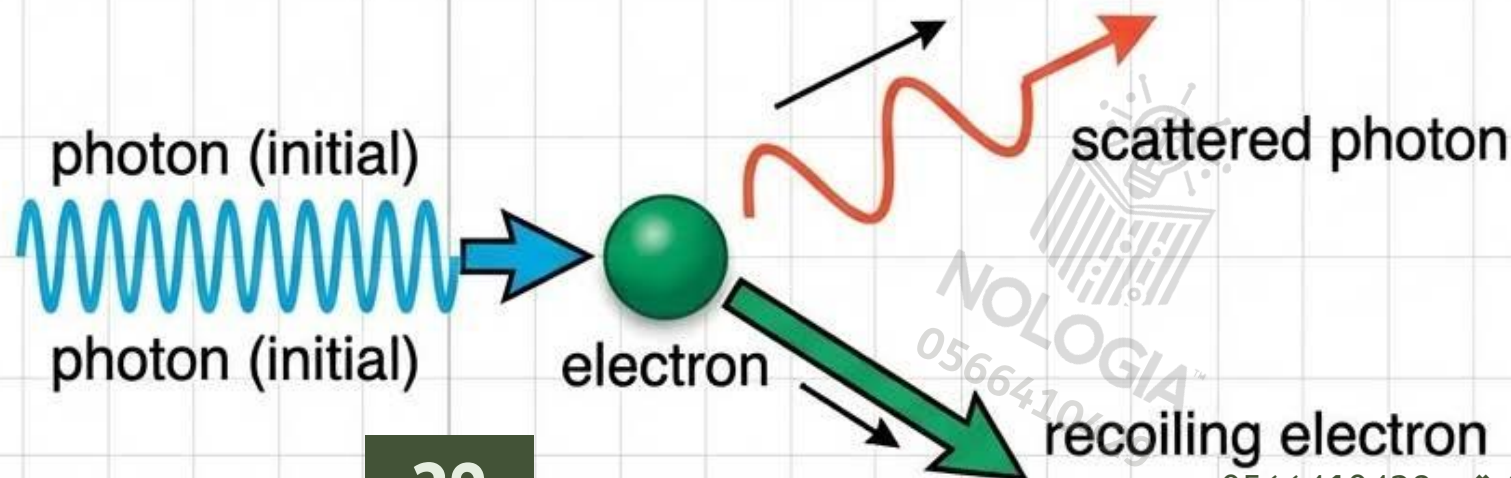
Concept: The Compton Effect (Momentum Without Mass)

Einstein predicted photons have momentum. In 1922, Arthur Holly Compton proved it by firing X-rays at graphite. Equation: $p = h/\lambda$.

Classical Collision

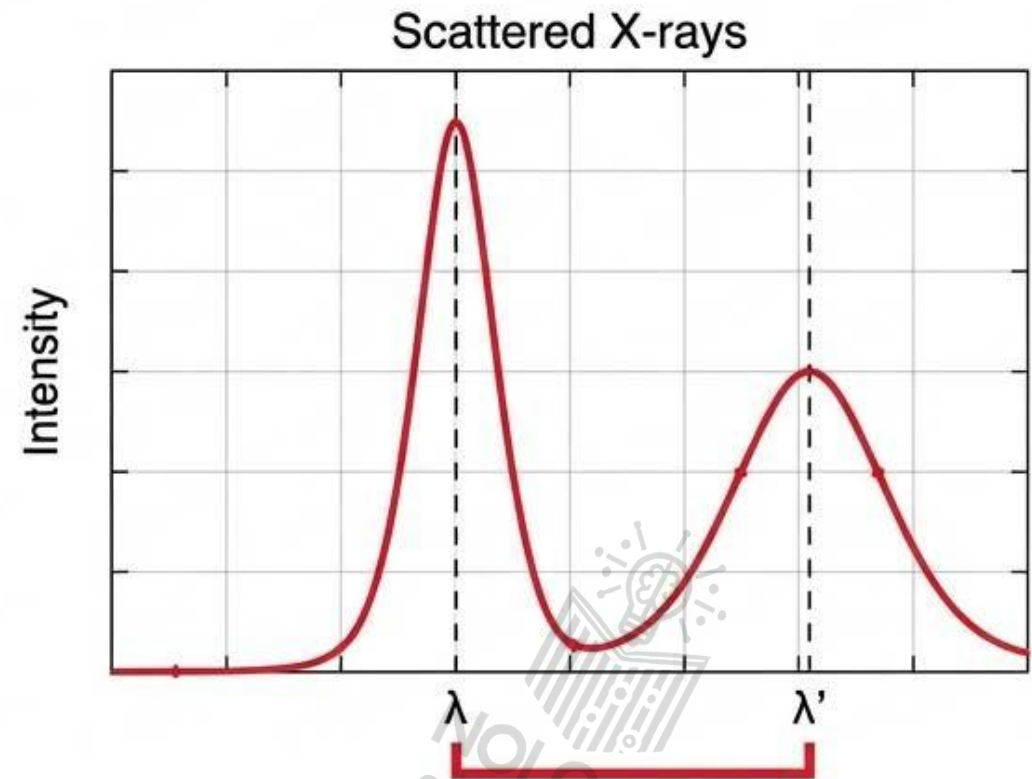
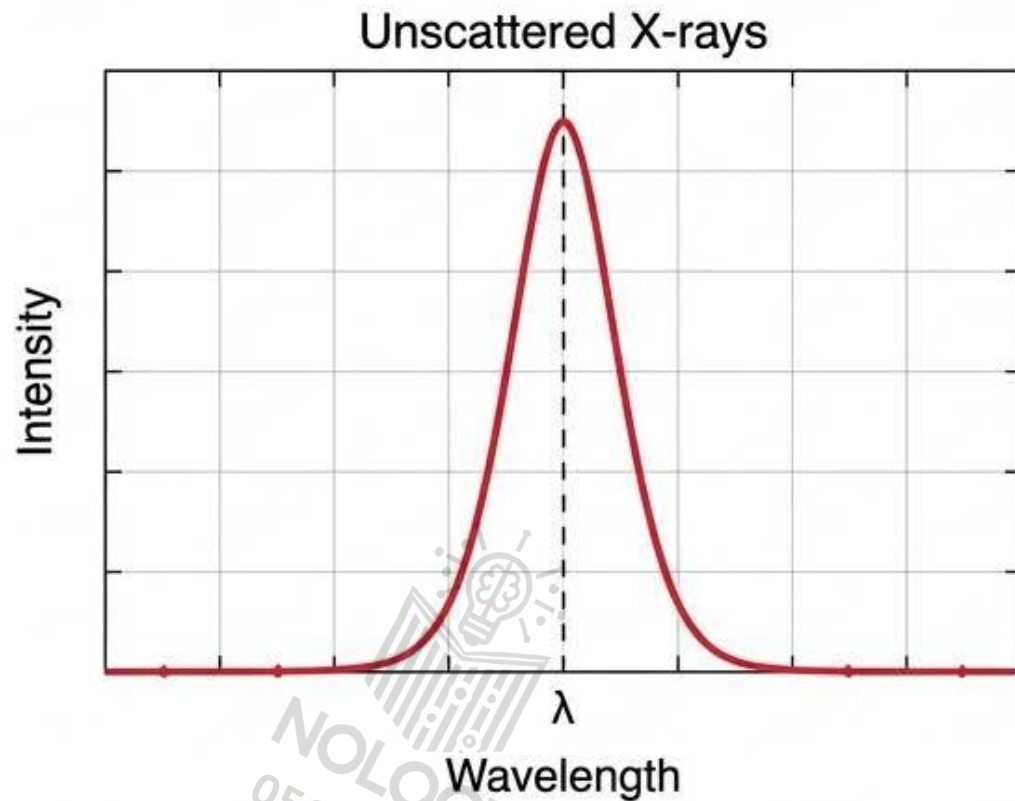


Quantum Collision:
Scattered photon loses energy, increasing its wavelength.



Analyzing the Compton Shift: Proof of Collision

Because energy and momentum are conserved, the energy gained by the recoiling electron must be lost by the photon. A loss in photon energy means a decrease in frequency, which results in an increase in wavelength.



The Compton Shift—Direct proof the massless photon transferred physical momentum.

Synthesis Matrix: Photoelectric vs. Compton Effects

	Photoelectric Effect	Compton Effect
Type of Incident Radiation	Visible / Ultraviolet Light	High-Energy X-Rays
What Happens to the Photon?	Completely absorbed and vanishes	Scattered and deflected with lower energy
Target Electron	Bound valence electrons	Free or loosely bound electrons
What this Phenomenon Proves	Light consists of discrete energy packets (particles)	These massless particles carry physical momentum

Mr. Mohamad's Master Equation Cheat Sheet

The Constants

$$h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$$
$$h = 4.14 \times 10^{-15} \text{ eV}\cdot\text{s}$$

$$c = 3.00 \times 10^8 \text{ m/s}$$
$$e = -1.602 \times 10^{-19} \text{ C}$$

Shortcut: $hc = 1240 \text{ eV}\cdot\text{nm}$

The Master Equations

Photon Energy:

$$E = hf = hc/\lambda$$

Photoelectric Effect:

$$KE = hf - hf_0$$

(or $KE = E - W$)

Stopping Potential:

$$KE = -e\Delta V_0$$

Compton Momentum:

$$p = h/\lambda = hf/c$$

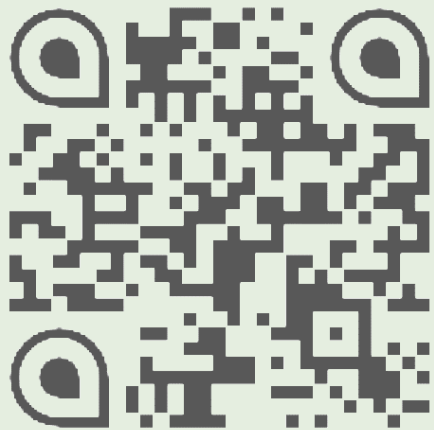
The Golden Rules

Rule 1: If calculating your final answer in eV, always use $h = 4.14 \times 10^{-15}$.

Rule 2: W (Work Function) and hf_0 are the exact same physical property.

Rule 3: Higher threshold frequency always means a higher work function.

End of Document. You are fully equipped for mastery.



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Module (22): Quantum Theory and the Atom

02

Second Lesson: Matter Waves



NOLOGIA™

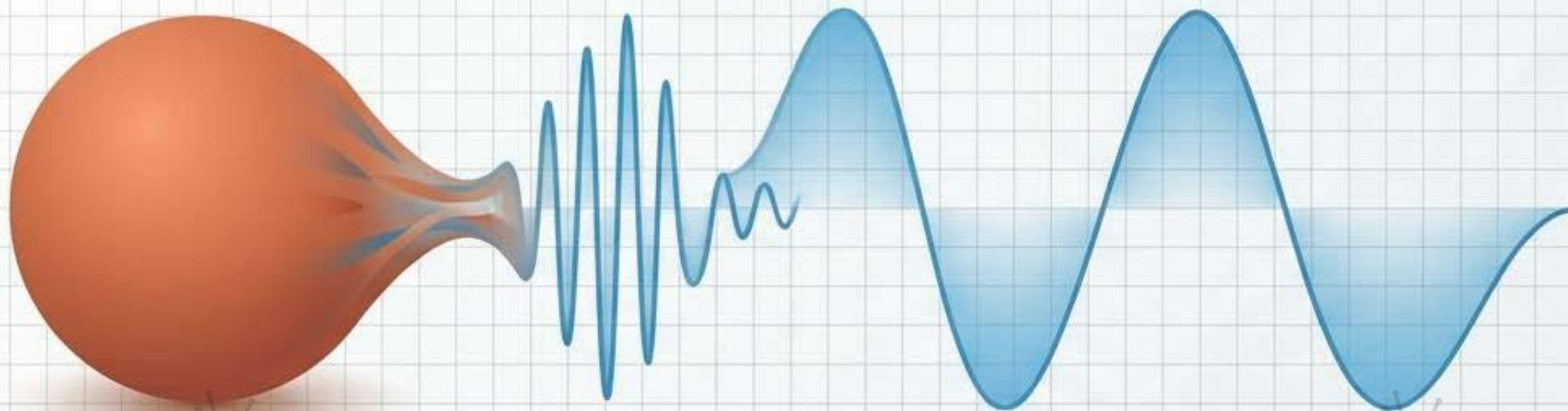


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Matter Waves & The Quantum Realm

A Comprehensive Physics Masterclass: From de Broglie to Heisenberg



Prepared Exclusively for mr.mohamad | Grade 12 Advanced Physics Study File

Einstein's Photon Theory



The Known: Electromagnetic waves can behave like a collection of particles (photons) with momentum ($p = h/\lambda$).

Louis de Broglie's Question (1923)



The Radical Proposal: If light waves act like particles, can material particles exhibit interference and diffraction as waves?

Bridging the Worlds: De Broglie proposed that moving particles have a momentum equivalent to photons, merging classical mechanics and the quantum realm.

de Broglie Wavelength

The resulting wave nature of the particle. Measured in meters (m).

Planck's Constant

The universal quantum scaling factor.
Value: 6.63×10^{-34} J.s.

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

Particle Momentum

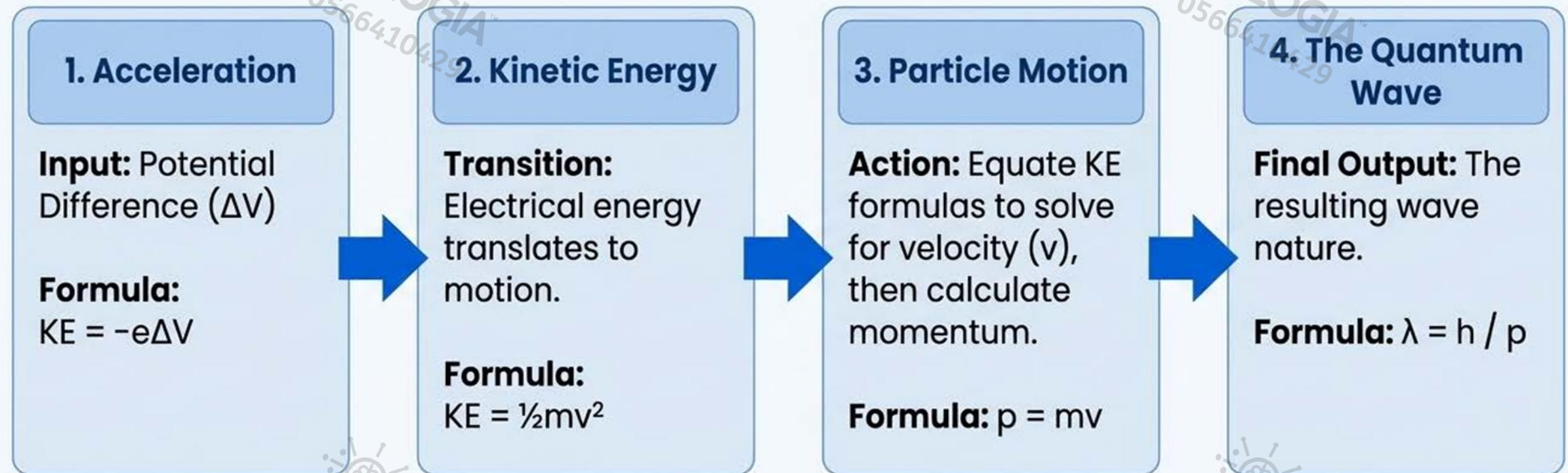
Mass (kg) multiplied by velocity (m/s).

Core Principle: The de Broglie wavelength of a moving particle is inversely proportional to its momentum. The bigger the momentum, the smaller the wave.

Why don't we see everyday objects acting like waves?

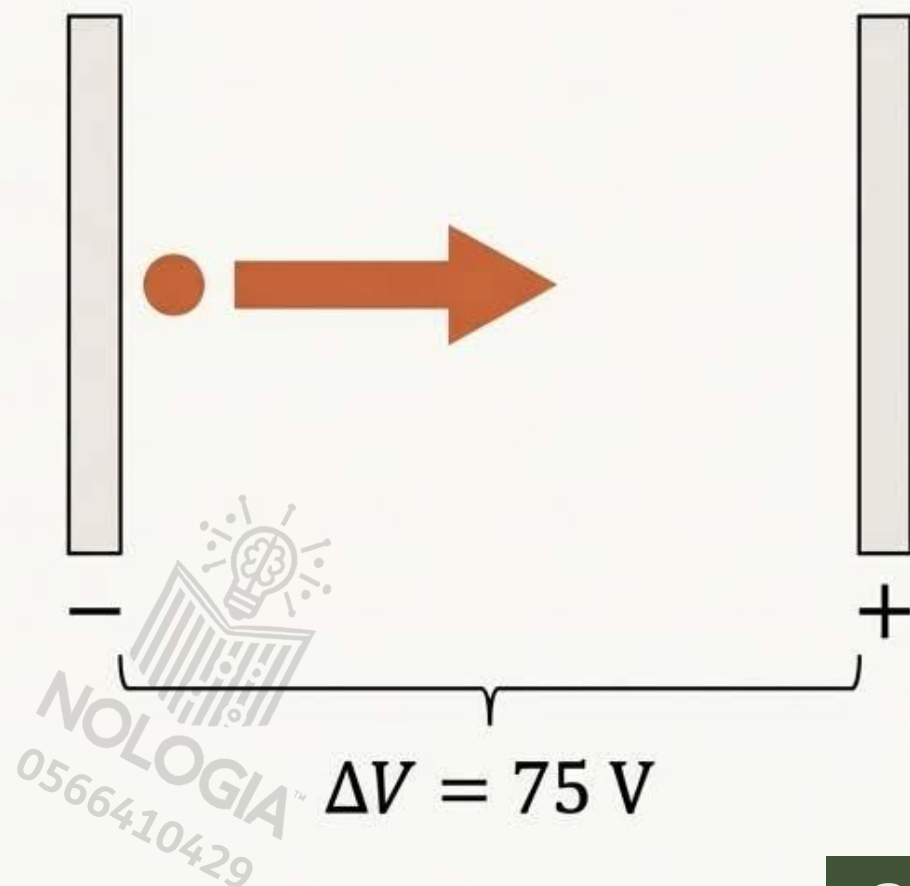
The Macroscopic Object	The Quantum Object
	
Mass (m): 0.145 kg	Mass (m): 9.11×10^{-31} kg
Velocity (v): 38 m/s	Velocity (v): 5.1×10^6 m/s
Wavelength (λ): 1.2×10^{-34} m	Wavelength (λ): 1.4×10^{-10} m (0.14 nm)
Verdict: Unobservable. Wavelength is infinitely smaller than the object itself. Wave properties are practically non-existent.	Verdict: Observable. Wavelength is comparable to atomic spacing, allowing measurable electron diffraction and interference.

The Equation Pipeline: Solving Quantum Mechanics Problems



By connecting electrical principles with mechanical motion, we can determine the invisible wavelength of any accelerated subatomic particle.

Core Example: Electron Acceleration Chamber



Data Ledger

Goal:
Find de Broglie wavelength ($\lambda = ?$)

Knowns:

- Voltage (ΔV) = 75 V
- Electron Mass (m_e) = $9.11 \times 10^{-31} \text{ kg}$
- Electron Charge (e) = $-1.602 \times 10^{-19} \text{ C}$
- Planck's Constant (h) = $6.63 \times 10^{-34} \text{ J}\cdot\text{s}$

Core Example: Step-by-Step Solution (75 V Electron)

Step 1: Calculate Velocity (v)

Equate electric potential energy to kinetic energy ($KE = -e\Delta V$ and $KE = 0.5mv^2$).

$$v = \sqrt{\frac{-2e\Delta V}{m}} \quad v = \sqrt{\frac{-2(-1.602 \times 10^{-19} \text{ C})(75 \text{ V})}{9.11 \times 10^{-31} \text{ kg}}}$$

$$v = 5.1 \times 10^6 \text{ m/s}$$

Step 2: Calculate Momentum (p)

Multiply the electron's mass by its newly found velocity.

$$p = mv \quad p = (9.11 \times 10^{-31} \text{ kg}) \times (5.1 \times 10^6 \text{ m/s})$$

$$p = 4.6 \times 10^{-24} \text{ kg}\cdot\text{m/s}$$

Step 3: Calculate Wavelength (λ)

Apply the de Broglie equation.

$$\lambda = \frac{h}{p} \quad \lambda = \frac{6.63 \times 10^{-34} \text{ J}\cdot\text{s}}{4.6 \times 10^{-24} \text{ kg}\cdot\text{m/s}} \quad \lambda = 1.4 \times 10^{-10} \text{ m}$$

(or 0.14 nm)

Dimensional analysis confirms units. 0.14 nm aligns with the X-ray region of the electromagnetic spectrum.

Comprehensive Examples: Practice Problem 26

The Math: The Bowling Ball

Setup: A 7.0-kg bowling ball rolls at 8.5 m/s. Find λ .

Calculation:

$$\lambda = \frac{h}{mv}$$

$$\lambda = \frac{6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{(7.0 \text{ kg})(8.5 \text{ m/s})}$$

Result:

$$\lambda = 1.1 \times 10^{-35} \text{ m}$$

The Analysis

Question: Why does the bowling ball exhibit no observable wave behavior?

The calculated wavelength (10^{-35} m) is **incomprehensibly** small—trillions of times smaller **than a single atom**. Interference and diffraction require wavelengths **comparable** to the size of the obstacles they interact with. At macroscopic scales, wave properties are strictly theoretical and mathematically irrelevant to everyday motion.

Comprehensive Examples: Practice Problem 25

Calculating the wavelength of an electron accelerated by a 250 V potential difference.

1. Velocity

$$v = \sqrt{\frac{-2(-1.602 \times 10^{-19})(250)}{9.11 \times 10^{-31}}}$$

$$= 9.38 \times 10^6 \text{ m/s}$$

2. Momentum

$$p = (9.11 \times 10^{-31}) \times (9.38 \times 10^6)$$

$$= 8.54 \times 10^{-24} \text{ kg}\cdot\text{m/s}$$

3. Wavelength

$$\lambda = \frac{6.63 \times 10^{-34}}{8.54 \times 10^{-24}}$$

$$= 7.76 \times 10^{-11} \text{ m}$$

$$(0.0776 \text{ nm})$$

Critical Comparison: Compared to the 75 V electron, increasing the voltage to 250 V increases the velocity. Because velocity and wavelength are inversely proportional, the higher voltage results in a significantly shorter wavelength.

The Limits of Measurement

Classical Physics



The Assumption of Infinite Precision

In the macroscopic everyday world, you can measure a falling object's location and velocity simultaneously to any desired level of precision. Improving the measurement is simply a matter of upgrading your equipment (e.g., higher-speed cameras, finer rulers).

Classical mechanics sets no theoretical limit on measurement accuracy.

Quantum Physics



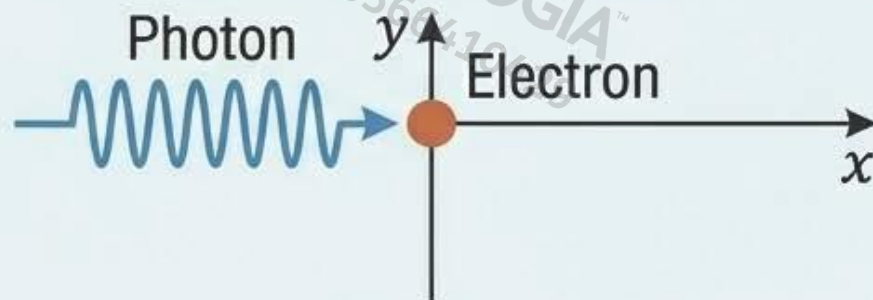
The Measurement Limit

To locate an atomic particle, you must bounce light off it. But light carries momentum. The very act of "looking" at a subatomic particle using a photon physically alters its trajectory.

Precision at this scale is no longer limited by human equipment; it is fundamentally bounded by the laws of physics.

The Mechanism of Uncertainty: The Compton Effect

Before Collision



Short-wavelength, high-energy radiation is required to pinpoint the electron's precise location.

After Collision



The collision scatters both particles. The photon's wavelength increases (it loses energy). The electron absorbs the impact, drastically altering its momentum.

Conclusion: The exact act of measuring the particle's location perfectly destroys your previous knowledge of its momentum.

The Heisenberg Uncertainty Principle (1927)

Low Precision of Momentum (Δp)

High Precision of Position (Δx)



- There is a fundamental limit to how precisely a particle's **position** and **momentum** can be known simultaneously.
- If you require a highly **precise** location, you must use **short-wavelength** light, which transfers massive energy and unpredictably alters the particle's momentum.
- If you want to leave the momentum undisturbed, you must use **long-wavelength** light, which provides a very blurry, inaccurate location.

This limit is not a failure of our tools; it is the **unavoidable consequence** of the **dual wave-particle nature of light and matter.**

The Quantum Blueprint: Master Reference Sheet

Final Review Document Prepared for mr.mohamad

Universal Constants & Values

Planck's Constant (h) = $6.63 \times 10^{-34} \text{ J} \cdot \text{s}$

Electron Mass (m_e) = $9.11 \times 10^{-31} \text{ kg}$

Elementary Charge (e) = $-1.602 \times 10^{-19} \text{ C}$

Proton Mass (m_p) = $1.67 \times 10^{-27} \text{ kg}$

Core Equations & Pipelines

de Broglie Wavelength: $\lambda = \frac{h}{p} = \frac{h}{mv}$

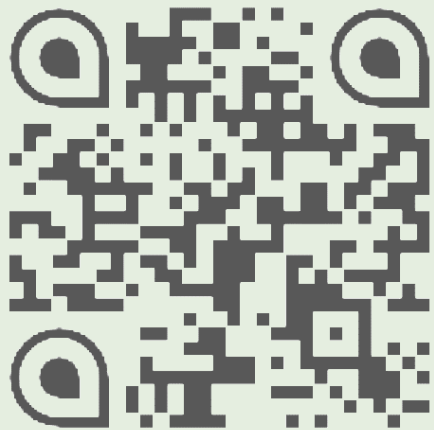
Kinetic Energy (from Voltage): $KE = -e\Delta V$

Kinetic Energy (from Motion): $KE = \frac{1}{2}mv^2$

Momentum: $p = mv$

The Golden Rule of Quantum Duality

- **Macroscopic Massive Objects:** Wavelengths are infinitely too small to observe. Classical physics applies perfectly.
- **Subatomic Objects (Electrons, Protons):** Observable wave behavior (diffraction, interference) requiring quantum mechanics.
- **The Uncertainty Trade-off:** You cannot simultaneously know both the precise location and precise momentum of a quantum particle.



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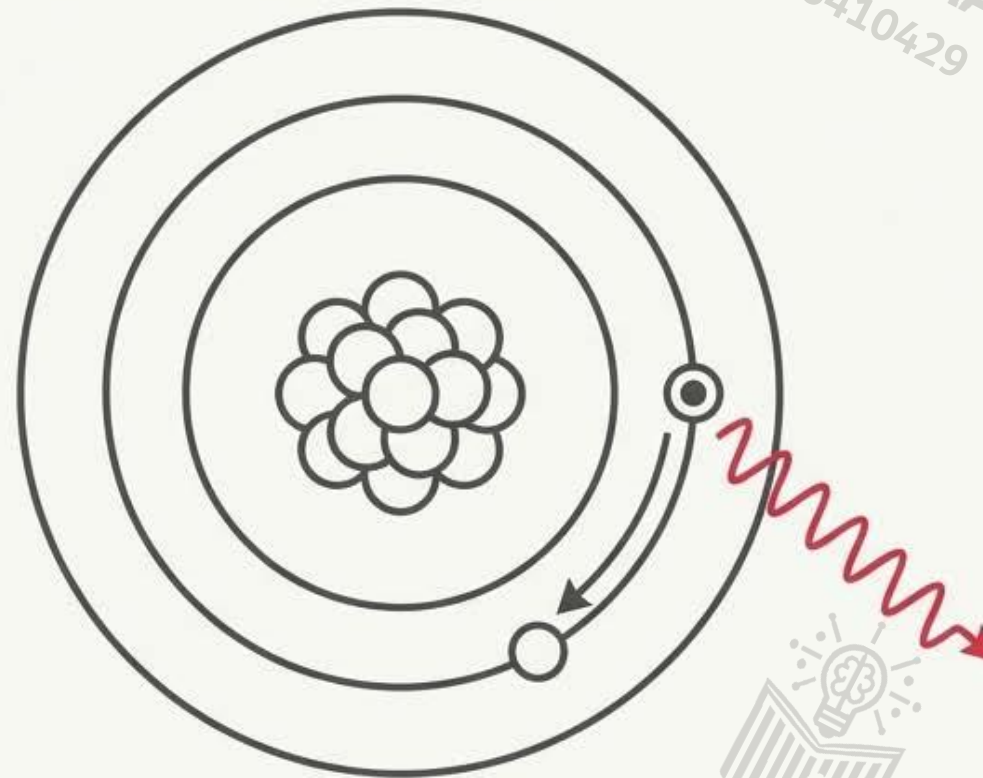
Module (22): Quantum Theory and the Atom

03

Third Lesson:
Bohr's Model of the Atom

The Architecture of the Atom

From Rutherford to
Bohr: A Comprehensive
Physics Study Guide

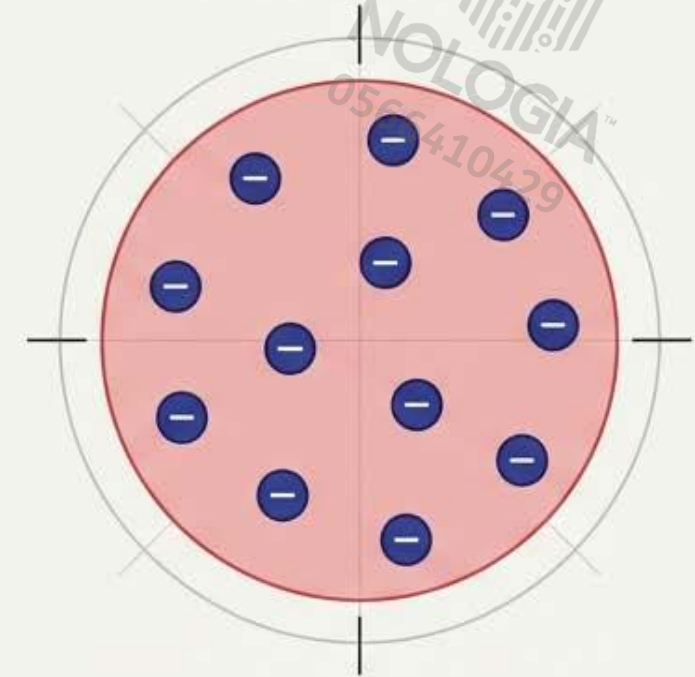


The Late 1800s: The Plum Pudding Baseline



The Metaphor

A positively charged dough interspersed with negatively charged pieces.



The Scientific Model

Electrons distributed randomly throughout a positively charged, massive substance.

- THE **KNOWNs**: Atoms are neutral and contain tiny electrons.
- THE **ASSUMPTION**: Mass and charge are evenly distributed.
- THE **BIG QUESTION**: How is the mass actually arranged?

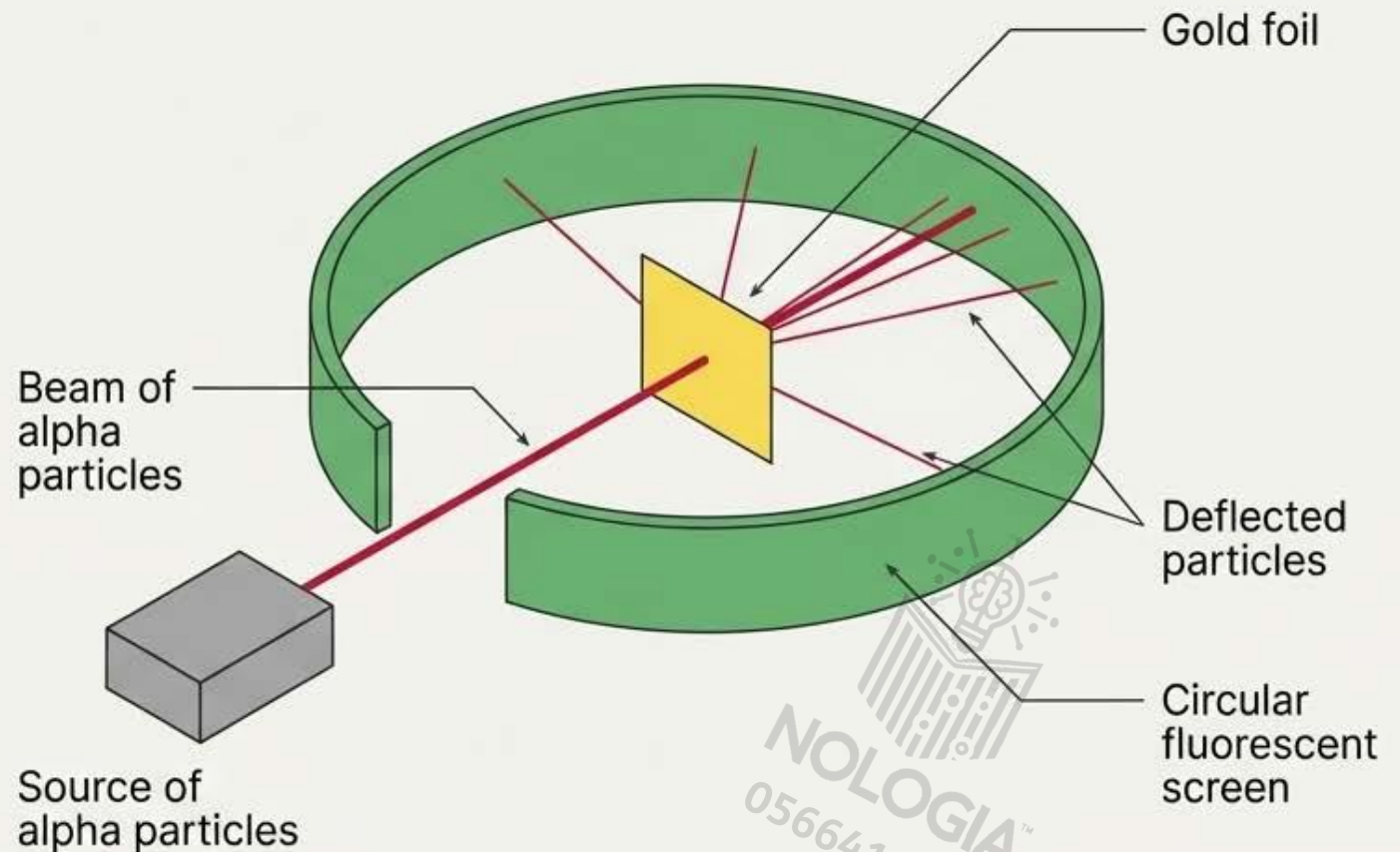
Testing the Theory: Firing Alpha Particles

THE SETUP

Ernest Rutherford directed massive, high-speed, positively charged alpha particles at an extremely thin sheet of gold foil.

THE EXPECTATION

If Thomson's evenly distributed model was correct, the massive alpha particles should pass straight through with almost no deflection.



The Cannonball Surprise

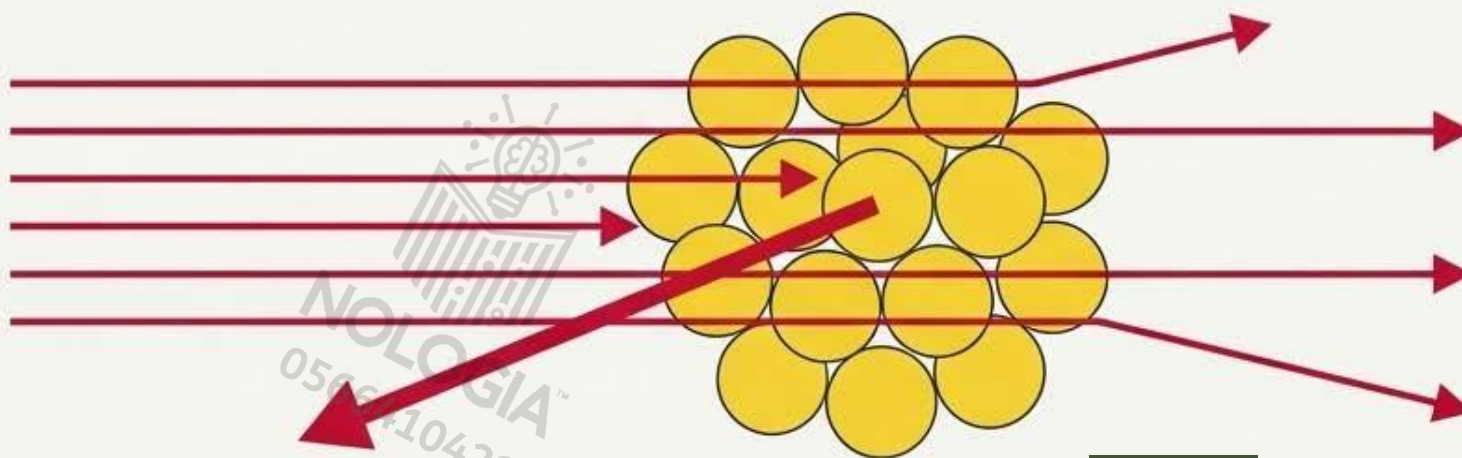
EXPECTATION: Thomson's Model



The Data

While most passed through, some deflected at large angles.
1 in 20,000 bounced almost straight back!

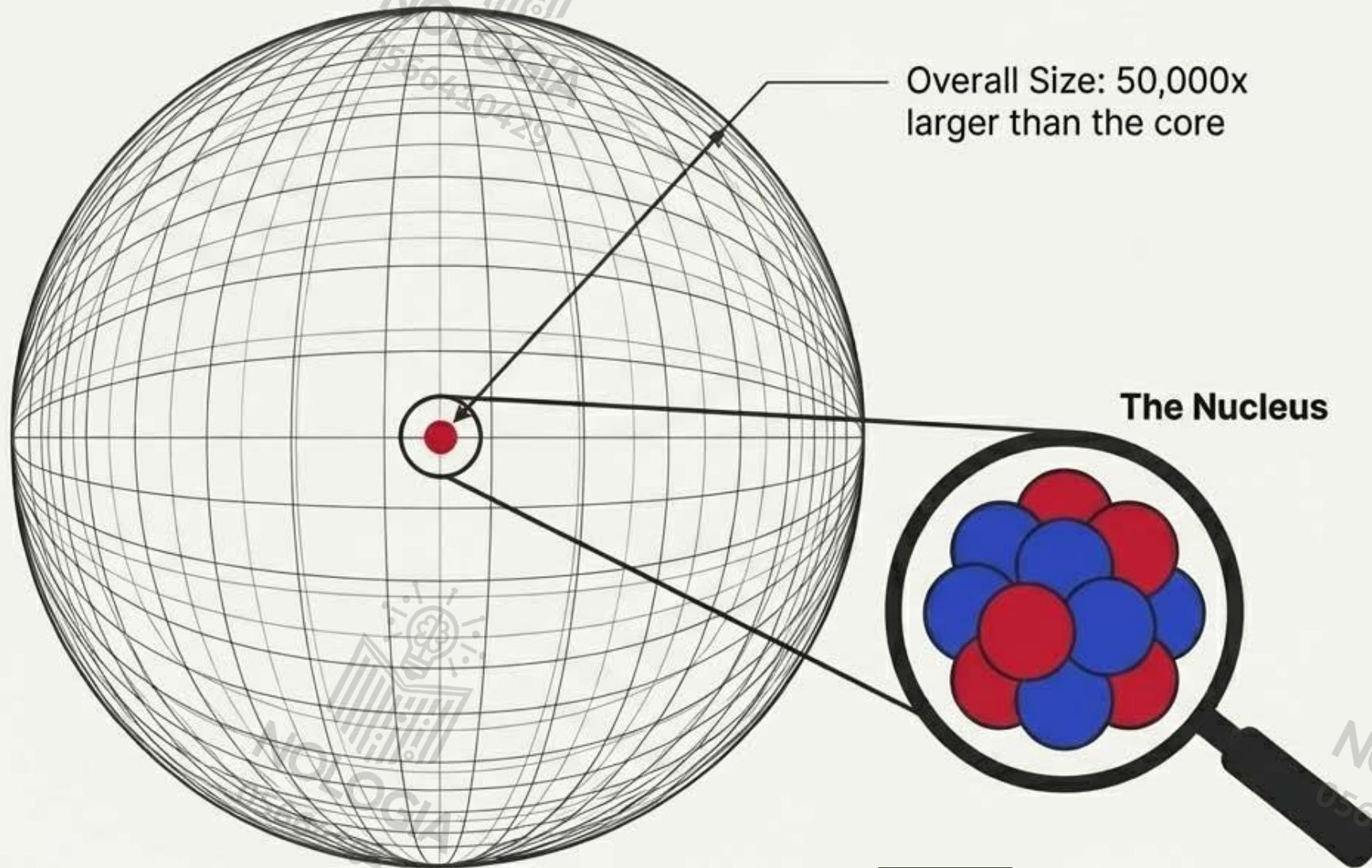
REALITY: Rutherford's Result



The Analogy

Rutherford compared it to firing a 15-inch cannon shell at a piece of tissue paper and having it bounce back to hit you.

The Discovery of the Nucleus



1. The Core

All positive charge and >99.9% of mass is concentrated in a tiny, dense core called the nucleus.

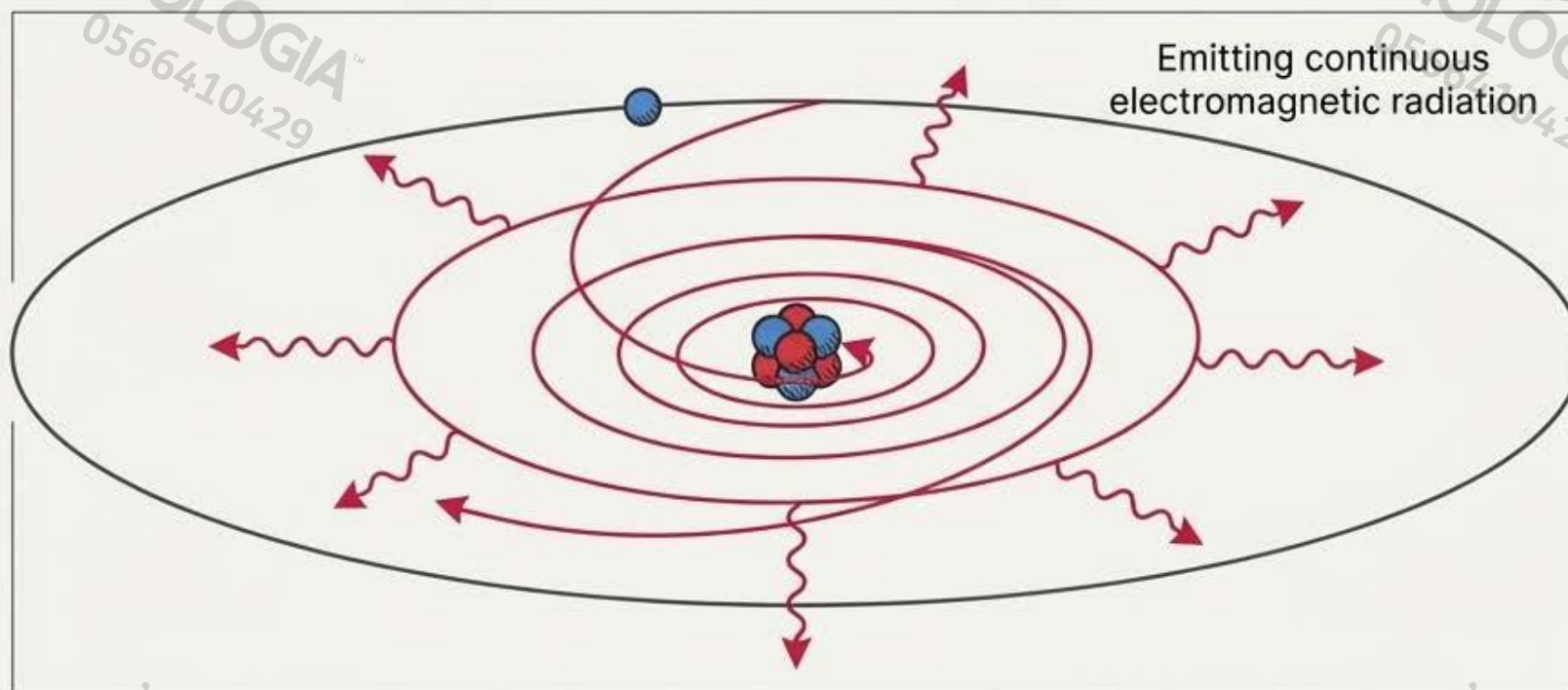
2. The Void

The overall volume is defined by orbiting electrons, a space 50,000 times larger than the nucleus.

CORE TAKEAWAY

The atom is almost entirely empty space.

The Physics Crisis: Why Doesn't the Atom Collapse?



THE PLANETARY MODEL

Rutherford imagined electrons orbiting like planets around a central sun.

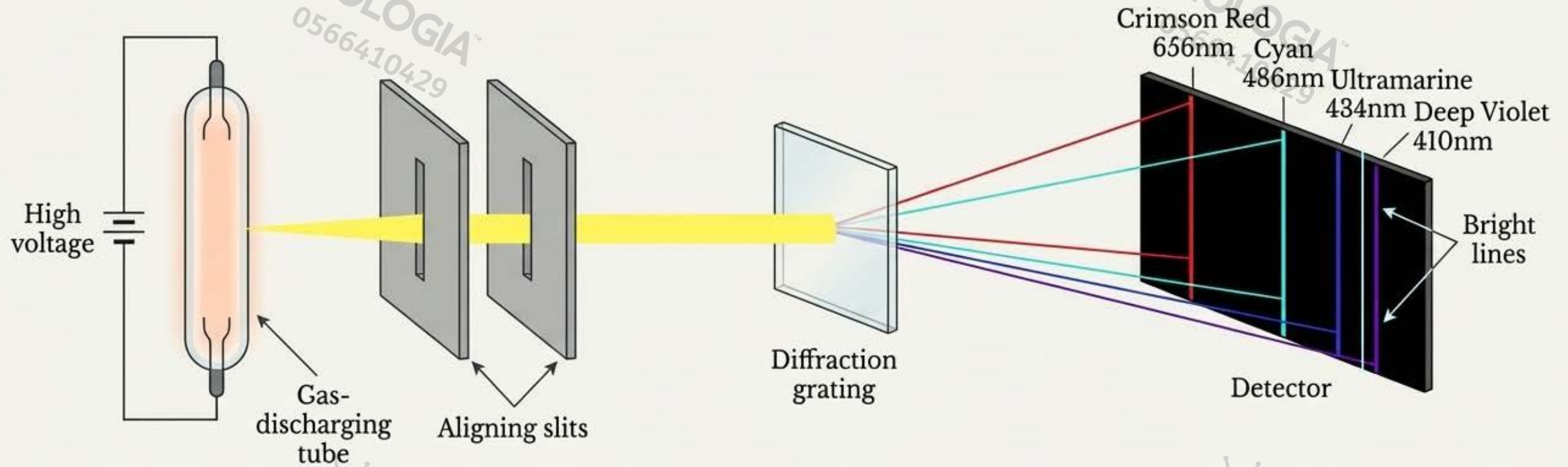
THE FATAL FLAW

Classical electromagnetism dictates that an accelerating charge (an orbiting electron) MUST radiate energy continuously.

THE CONSEQUENCE

The electron should lose speed, spiral into the nucleus in a fraction of a second, and collapse. But atoms are stable. The model was incomplete.

Clues from Light: Emission Spectra



THE PHENOMENON

When high voltage is applied to a low-pressure gas, it glows intensely (like a neon sign).

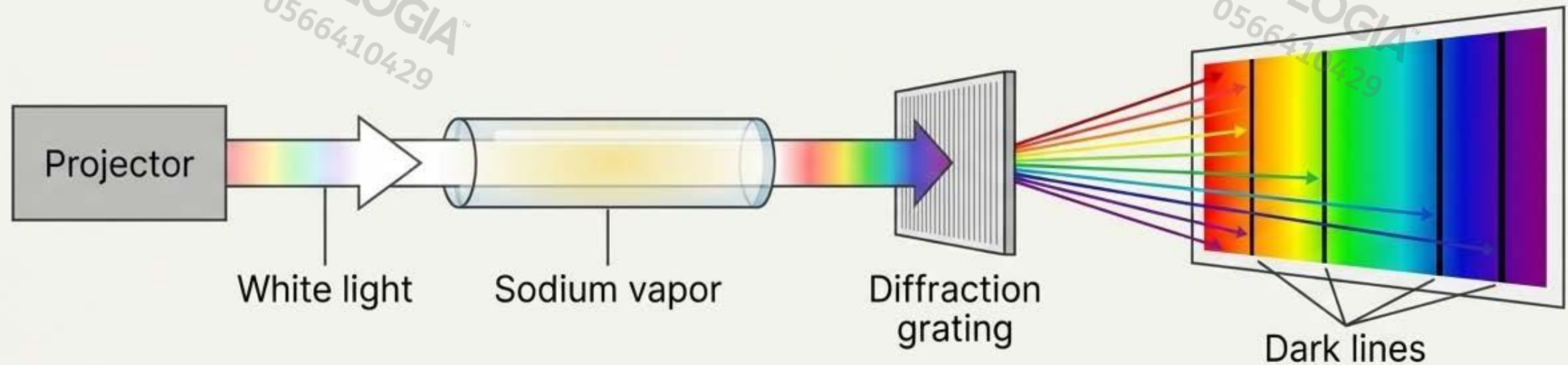
THE REVELATION

Passing this emitted light through a diffraction grating does not produce a continuous rainbow. It produces an Emission Spectrum: distinct, bright lines.

THE FINGERPRINT

Every element emits a uniquely characteristic set of colored lines. Mercury's barcode looks completely different from Neon's.

The Missing Pieces: Absorption Spectra



THE PHENOMENON

Passing continuous white light through a cool gas produces a nearly continuous spectrum—but with highly specific dark lines missing.

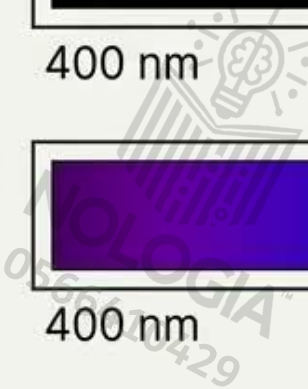
THE RULE OF SYMMETRY

Cool gaseous elements absorb the exact same wavelengths of light that they emit when excited! The missing black lines correspond perfectly to the bright emission lines.

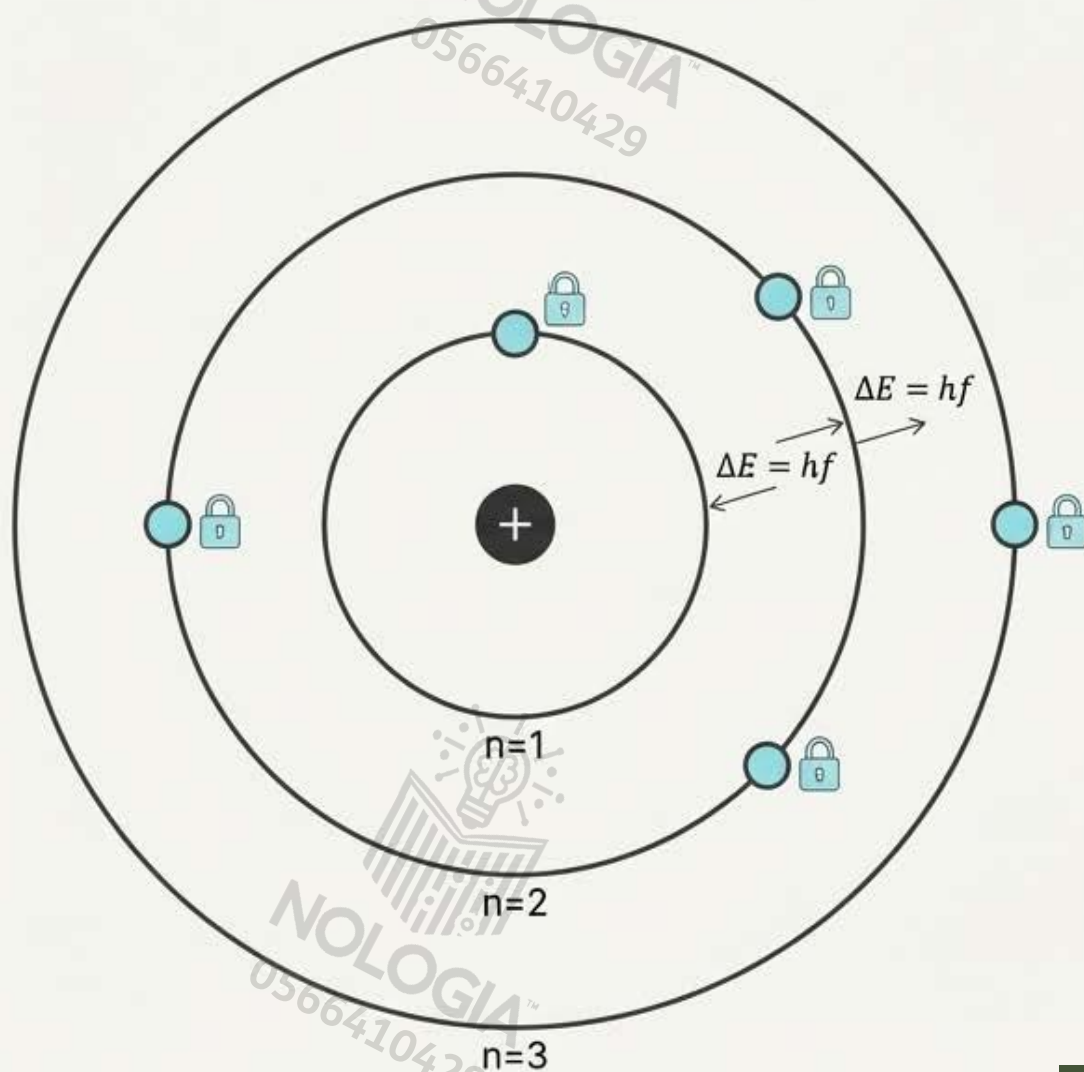
N MAT

Em

Light passing through



1911: Bohr Unites the Atom and Quantum Theory



THE POSTULATE

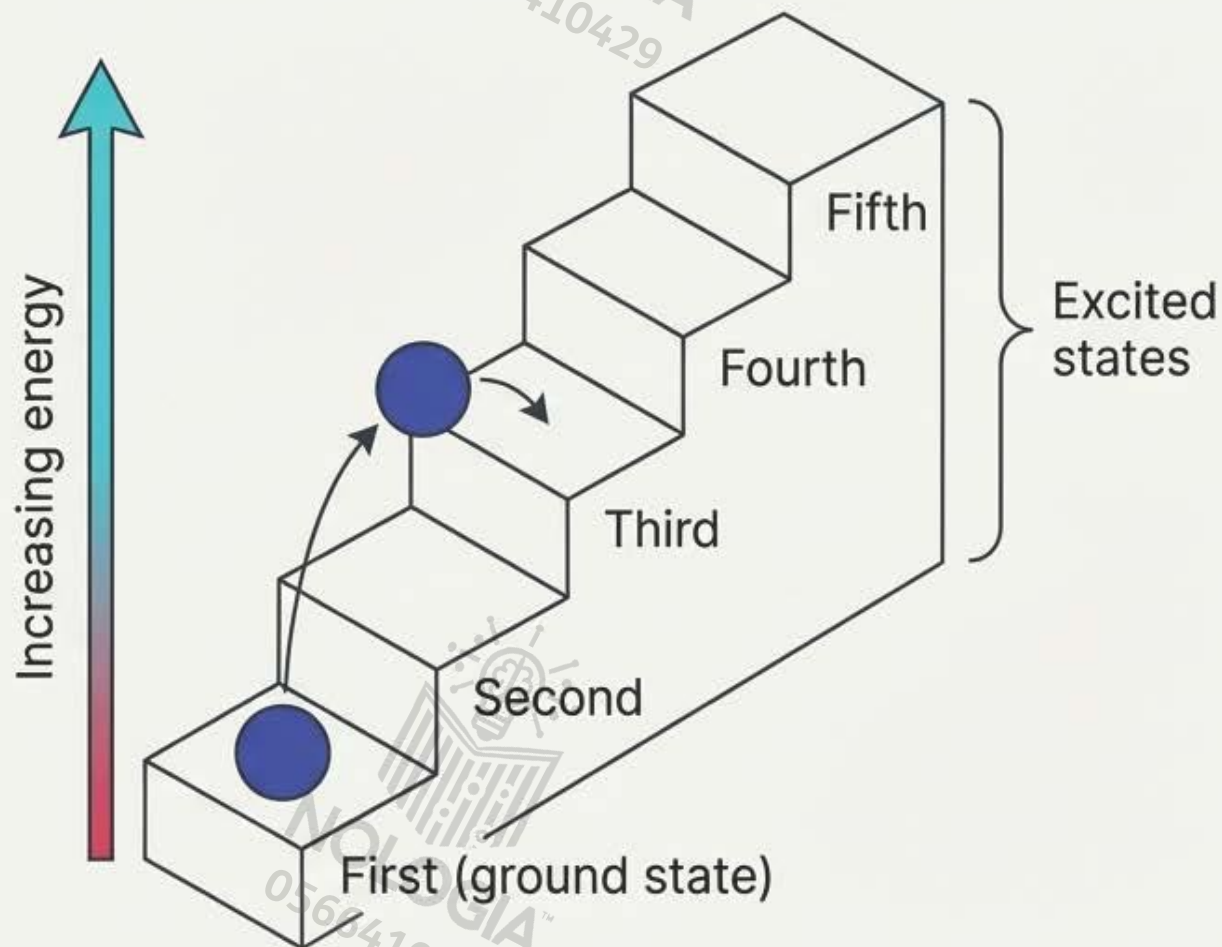
Danish physicist Niels Bohr proposed that electrons in stable orbits do not radiate energy, defying classical electromagnetism. He defined these as stationary states.

THE BREAKTHROUGH

Energy in the atom is quantized. An atom can only possess specific, strictly allowed amounts of energy, which uniquely dictate the exact size of the electron's orbit.

$$E_n = -\frac{R_H}{n^2}$$

Understanding Quantized Energy Levels



THE STAIRCASE ANALOGY

Just as you cannot stand hovering between steps on a staircase, an electron's energy cannot have a value between allowed levels.

GROUND VS EXCITED

Ground State: The smallest allowable amount of energy (the first step).

Excited State: Any energy level above the ground state. When atoms absorb energy, electrons move to these higher steps.

KEY DETAIL

Notice how the energy difference (the height) between adjacent levels decreases as total energy increases!

The Mathematics of the Quantum Jump

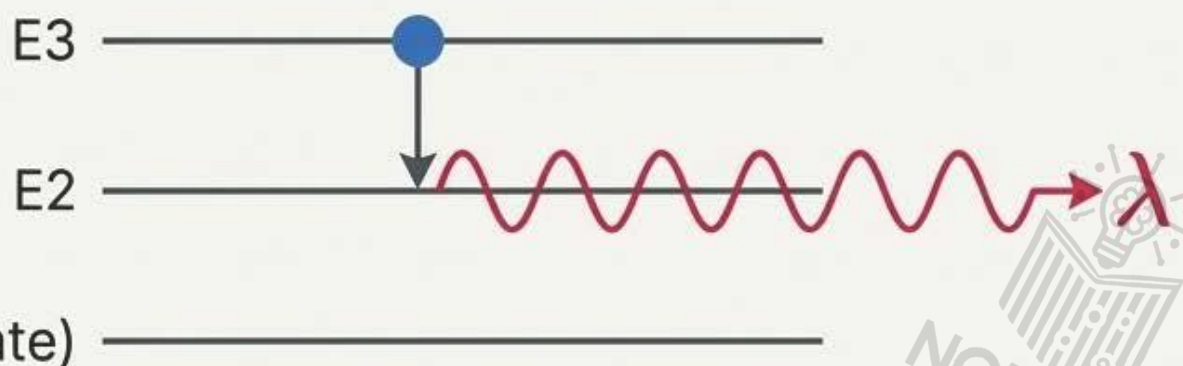
$$E_{\text{photon}} = hf = -\Delta E_{\text{atom}} = E_i - E_f$$

E_{photon} : Energy of emitted light

h : Planck's constant

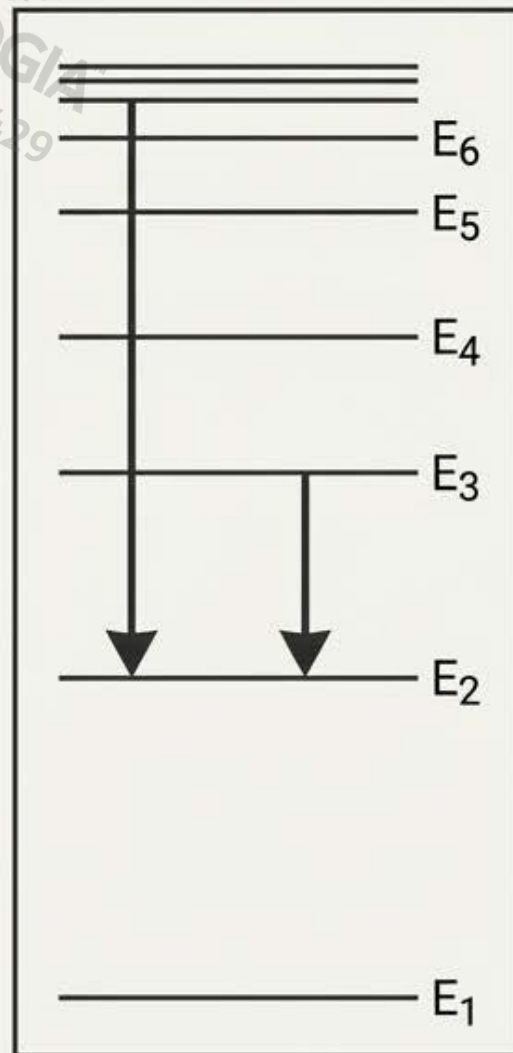
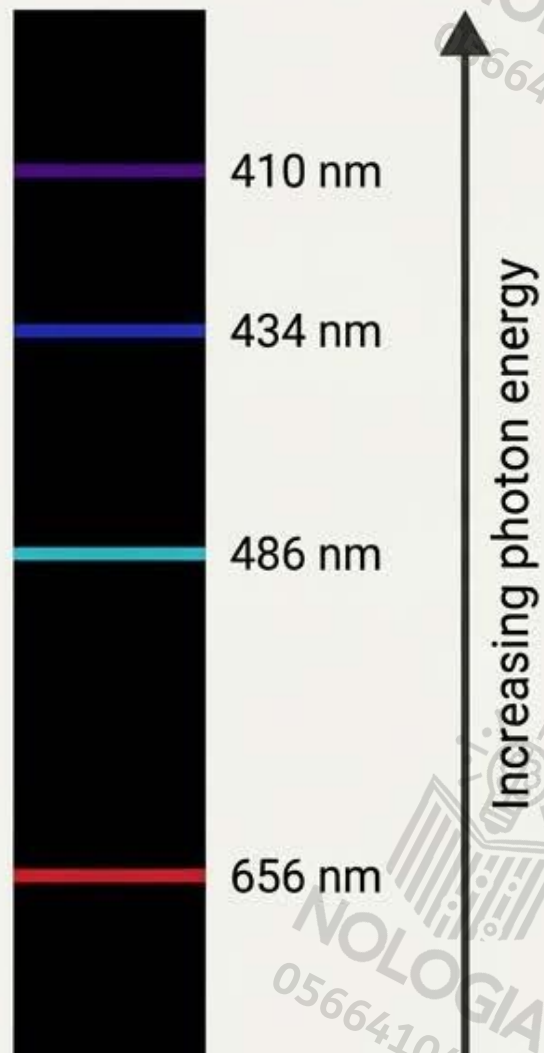
f : Frequency of the photon

$E_i - E_f$: Initial energy minus final energy of the atom



When an excited atom transitions from a higher energy level to a lower one, it emits a photon. The photon's energy exactly equals the energy lost by the atom.

Solving the Hydrogen Mystery



THE SYNTHESIS

Why does Hydrogen, the simplest element, have exactly four visible lines? Because those lines correspond to exact, quantized energy transitions within the atom.

THE RULE OF ENERGY

Larger energy drops emit photons with higher frequency and shorter wavelengths (Violet - 410nm).

Smaller energy drops emit photons with lower frequency and longer wavelengths (Red - 656nm).

Spectroscopy in Action

The study of spectra is the ultimate analytic tool across disciplines.



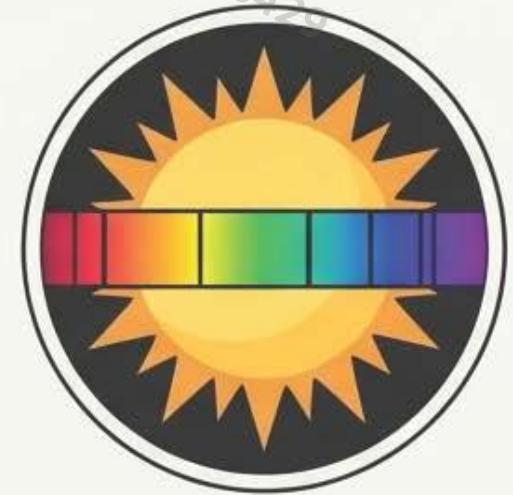
Industry

Steel mills analyze the exact composition of scrap iron in minutes via spectrographic analysis to adjust mixtures to commercial specifications.



Medicine & Environment

Scientists identify unknown trace elements and gaseous mixtures in complex environmental samples based on their emission fingerprints.



Astronomy

Matching dark lines in starlight to known emission spectra proved the Sun is mostly Hydrogen and Helium. It is our only tool for studying star composition across the expanse of space.

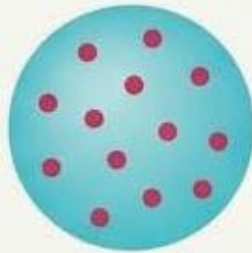
The Evolution of the Atomic Model (Cheat Sheet)

J.J. Thomson (Late 1800s)

Plum Pudding Model

Core Idea:

Positive mass blob with embedded negative electrons.



Fatal Flaw:

Disproved by Rutherford's large-angle alpha particle deflections.

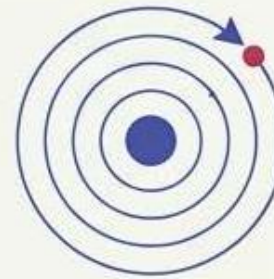


Ernest Rutherford (1911)

Nuclear / Planetary Model

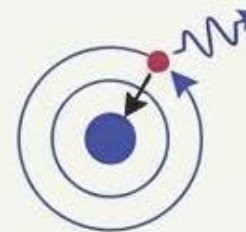
Core Idea:

Tiny, dense positive nucleus; atom is >99.9% empty space.



Fatal Flaw:

Accelerating orbiting electrons should radiate energy and crash into the nucleus.

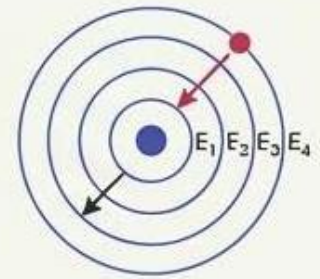


Niels Bohr (1911)

Quantum Model

Core Idea:

Quantized energy levels, stationary states. Electrons don't radiate while in orbit.



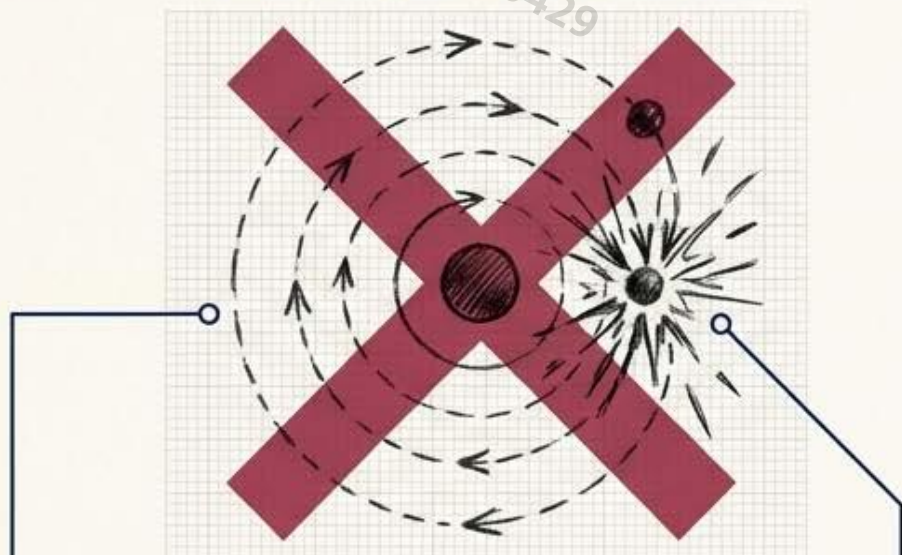
Triumph: Perfectly mathematically explains the emission spectra (fingerprints) of elements!



CORE RULE: $E_{\text{photon}} = hf = E_i - E_f$. Energy is quantized. Spectra are fingerprints.

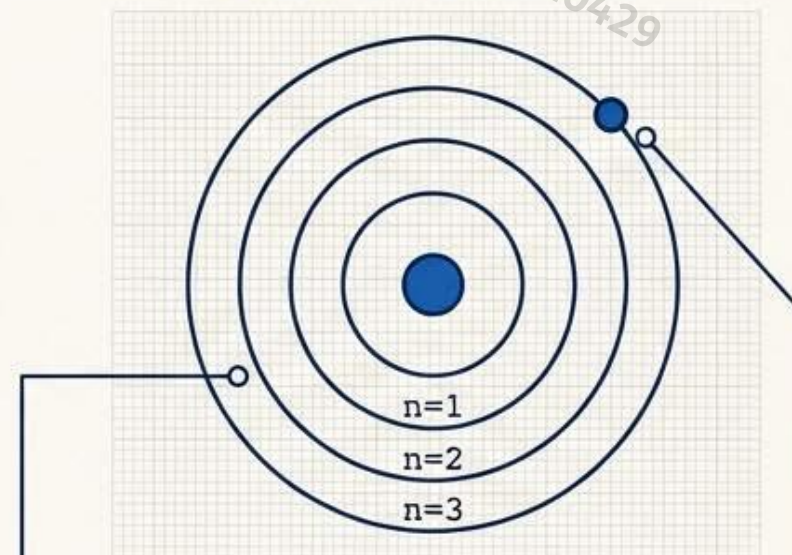
Classical Physics Predicted the Collapse of Matter

Classical Expectation



According to classical electromagnetism, an orbiting electron should constantly radiate energy, lose speed, and immediately spiral into the nucleus.

Bohr's Solution



Bohr hypothesized that electrons exist only in specific, stable orbits without radiating energy.

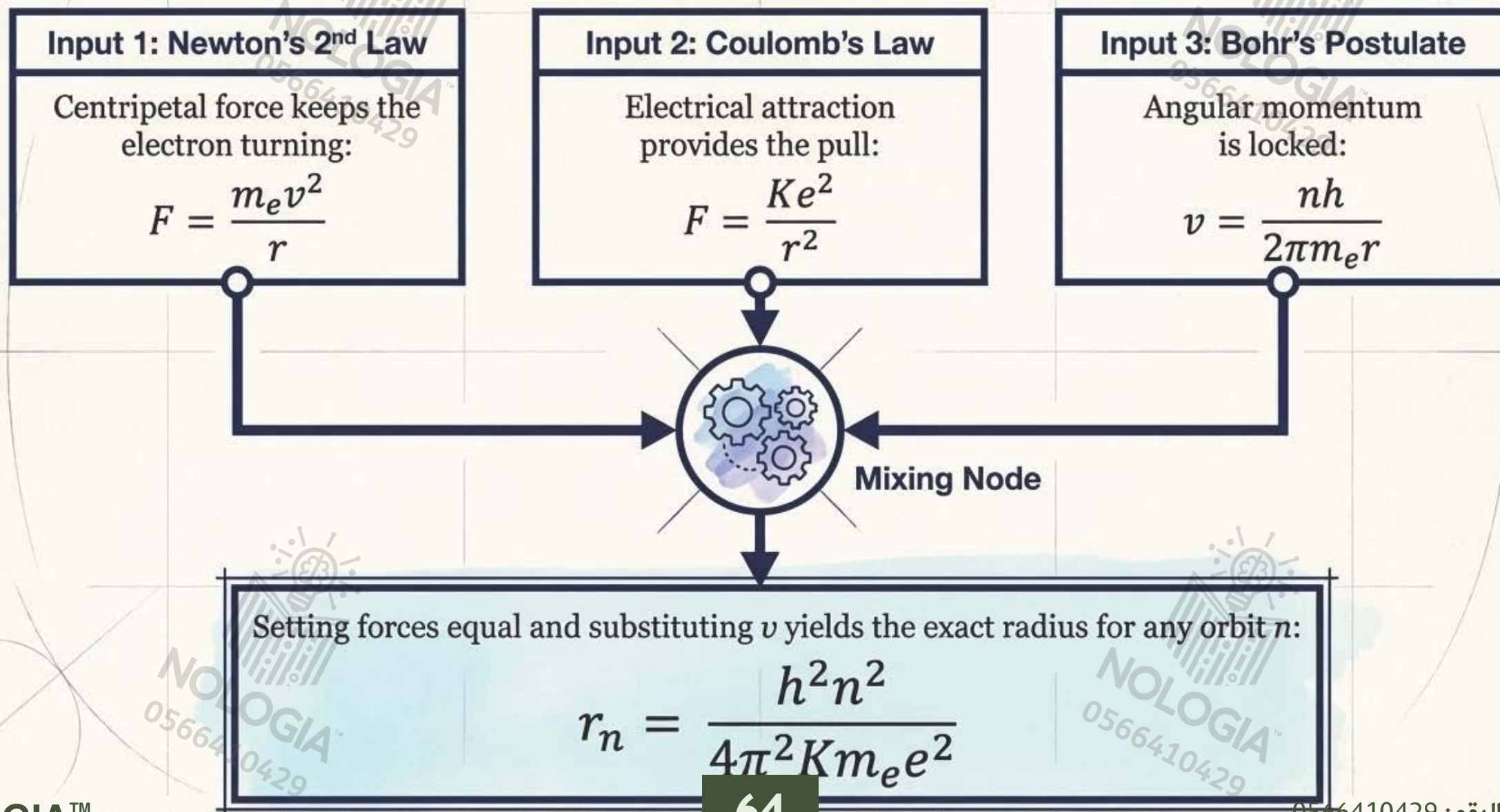
The Core Postulate

Angular momentum is quantized. Bohr proposed that an electron's angular momentum can only be specific integer multiples of Planck's constant:

$$m_e v r = \frac{n h}{2 \pi}$$

(where n is an integer 1, 2, 3...)

Deriving the Architecture: Where the Electron Lives



The Principal Quantum Number (n) Controls the Radius

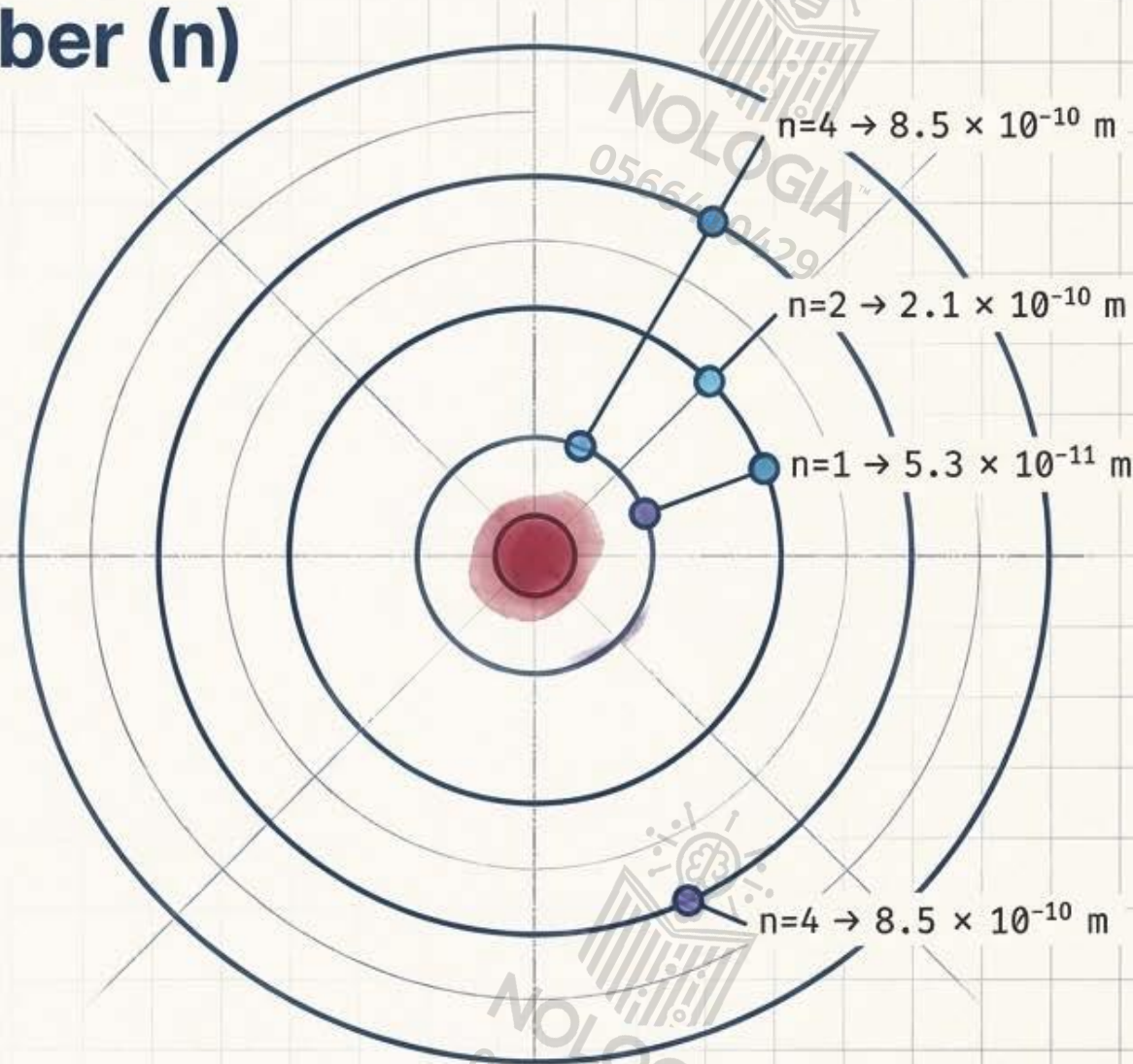
The complex collection of constants collapses into a single baseline value when $n=1$. This is the innermost orbit, or the Bohr radius.

Key Value

Ground State Radius (r_1) = $5.3 \times 10^{-11} \text{ m}$

The Shortcut Formula

$$r_n = r_1 \times n^2$$



Deriving the Architecture: The Energy Well

Concept Breakdown

Total Energy = Kinetic Energy + Potential Energy

The Master Energy Formula:

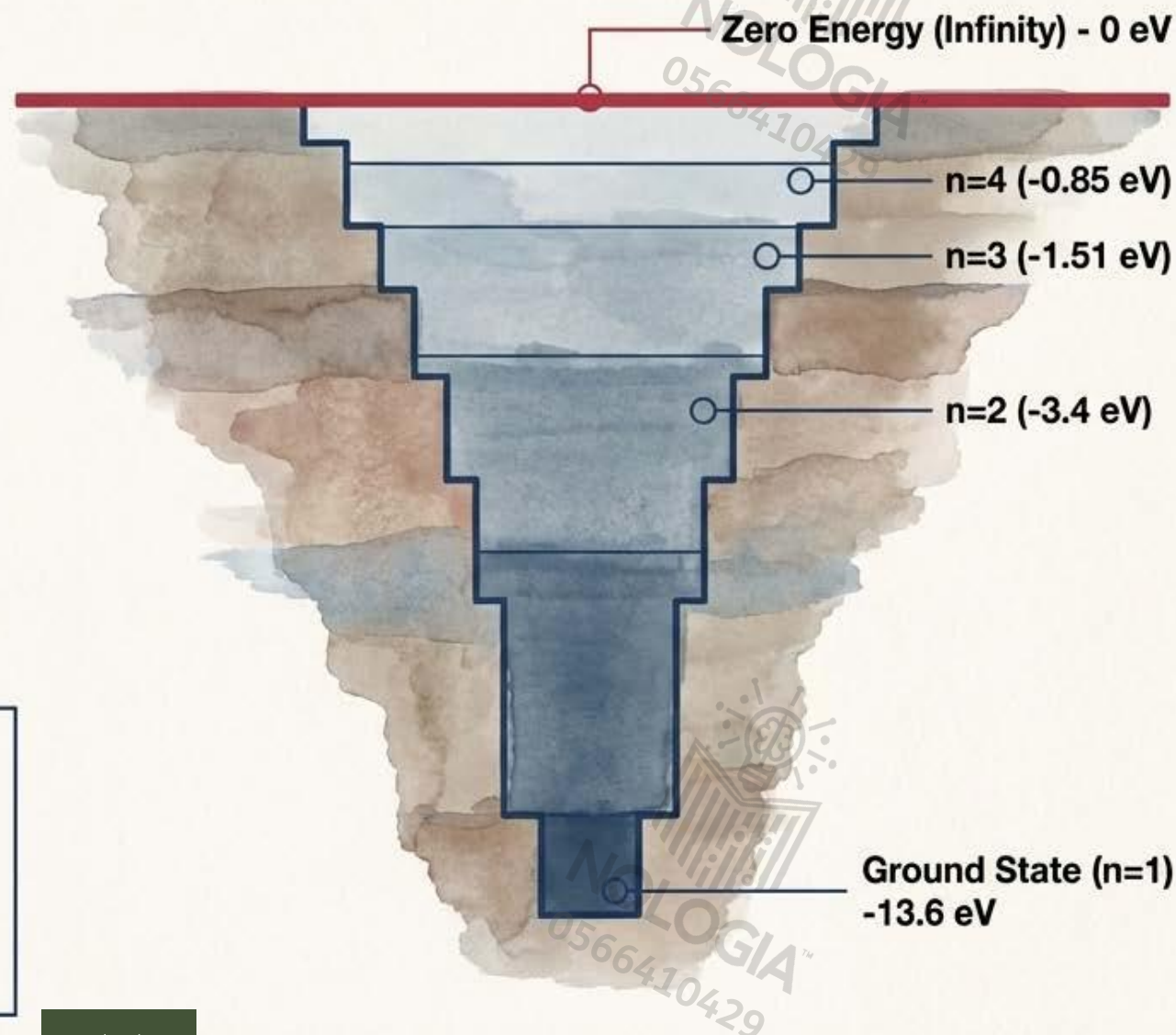
$$E_n = \frac{-2\pi^2 K^2 m_e e^4}{h^2} \times \frac{1}{n^2}$$

The Shortcut Formula

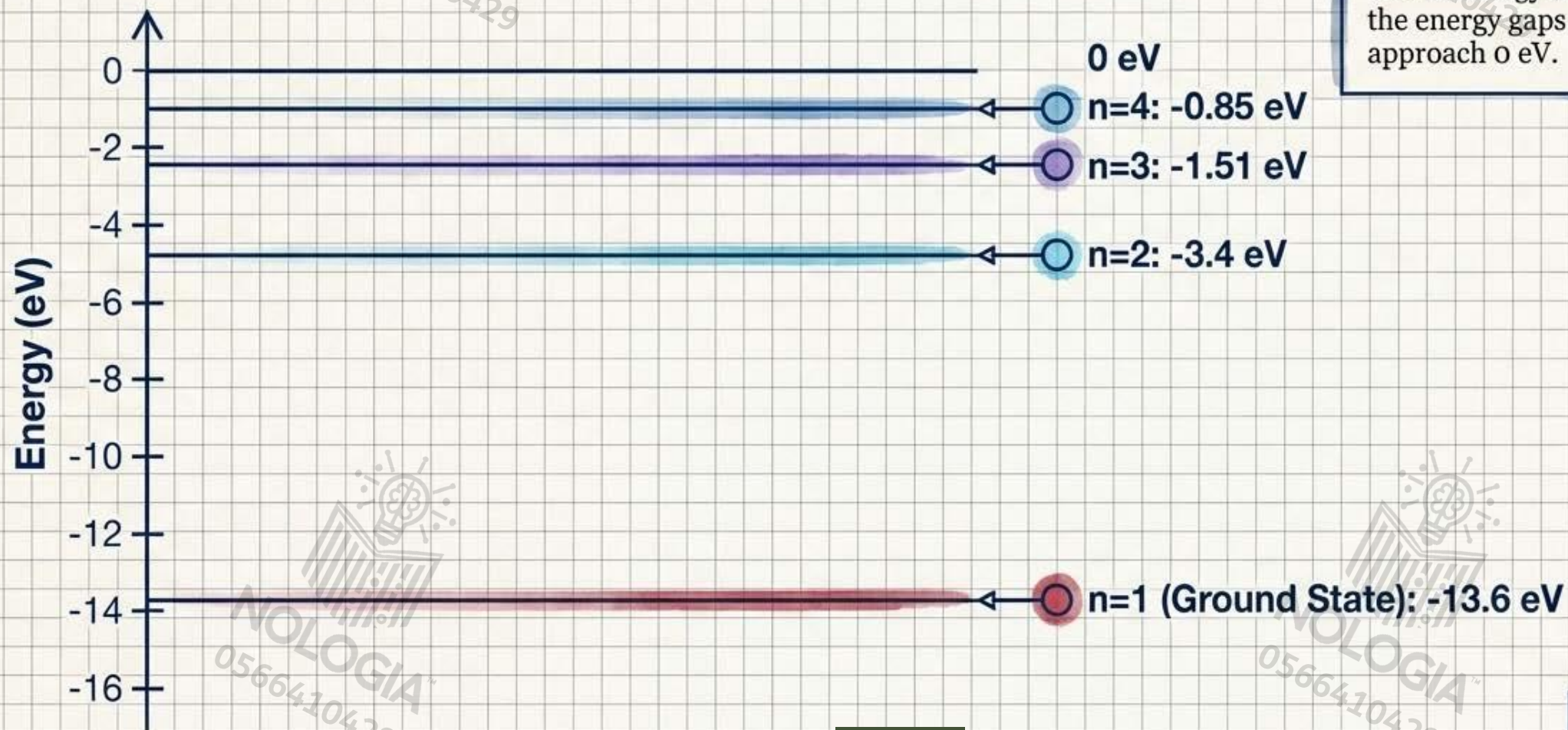
$$E_n = -13.6 \text{ eV} \times \frac{1}{n^2}$$

Why is Energy Negative?

Zero energy is defined as the state where the electron is completely ionized (infinitely far from the nucleus with no kinetic energy). Because it requires work to pull an electron out of its orbit up to zero, the trapped orbiting electron always has less than zero energy. It is in an energy "debt".



Mapping the Energy States of Hydrogen



Key Insight

The ground state ($n=1$) requires the most energy to escape. As n increases, the magnitude of the atom's energy decreases, and the energy gaps shrink as they approach 0 eV.

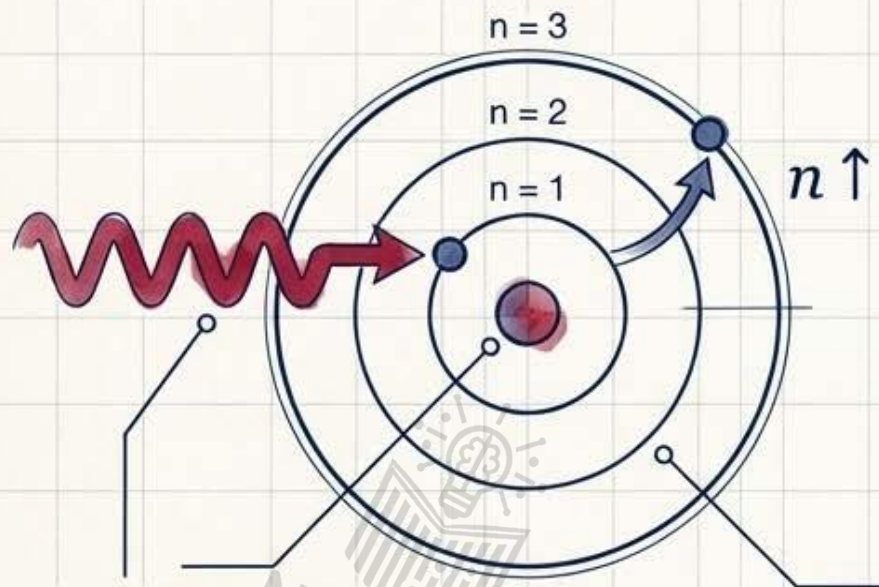
The Physics of Light: Energy Transitions

The Golden Rule

$$\Delta E = E_f - E_i$$

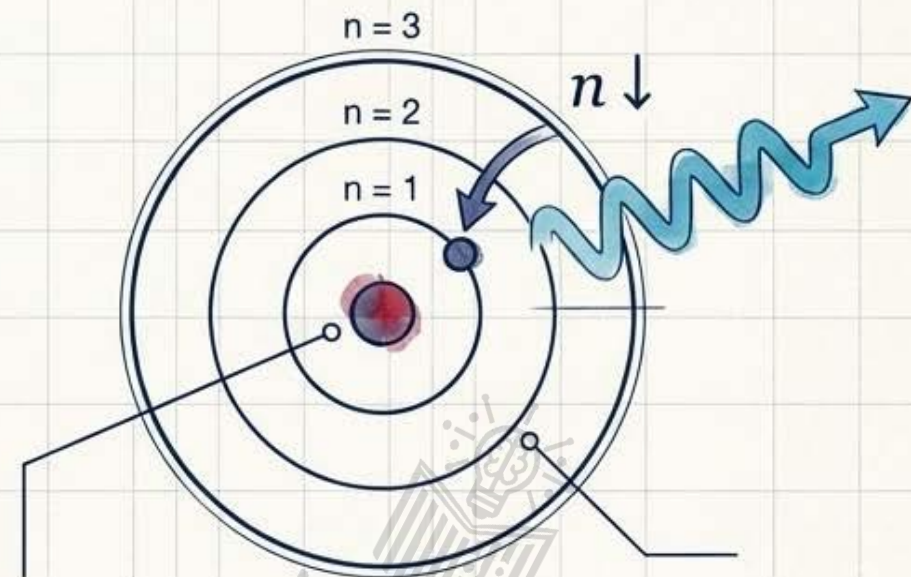
Only differences in energy states can be absorbed or emitted.

Absorption



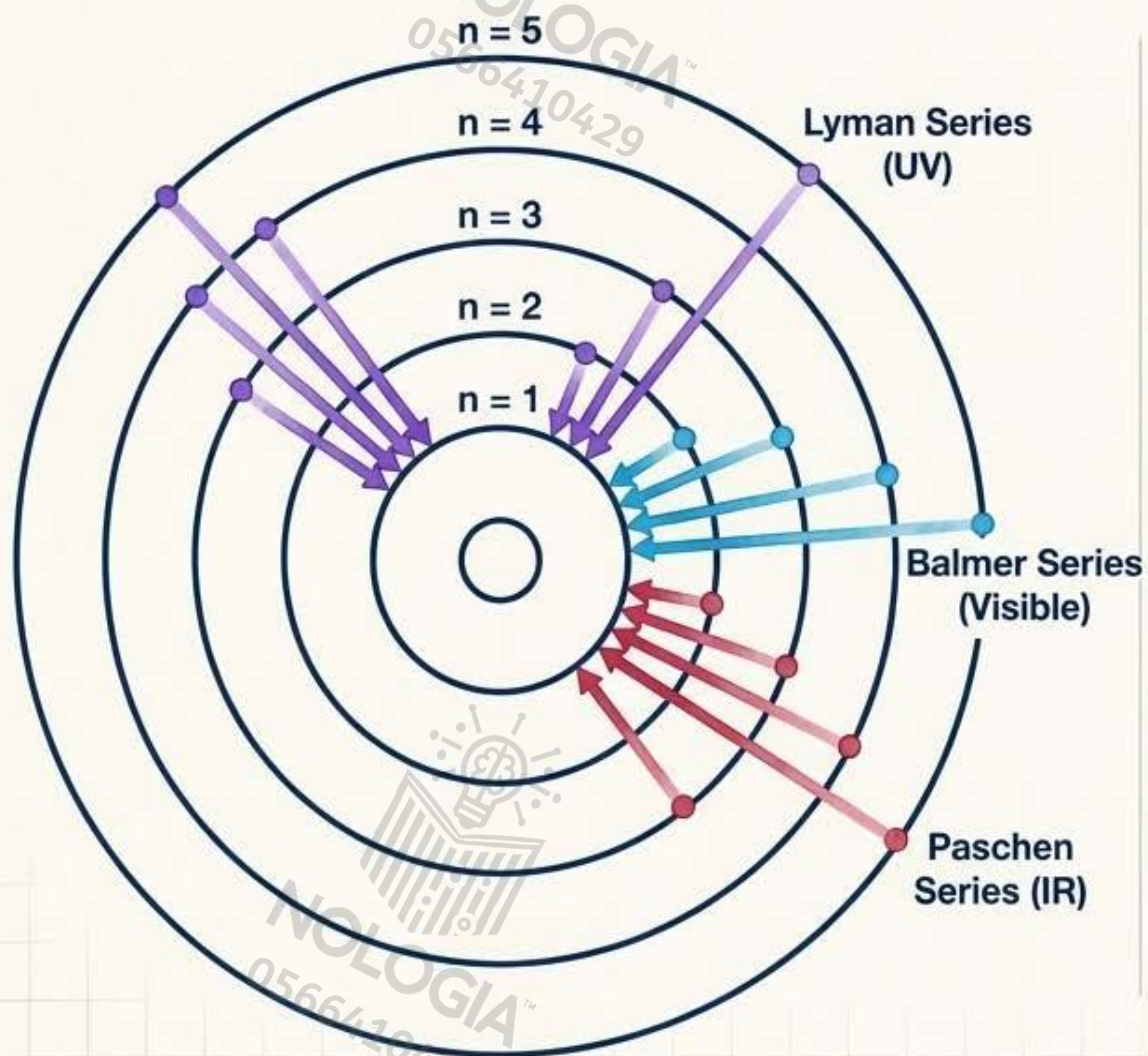
- Photon Absorbed
- Electron moves UP
- ΔE is Positive

Emission



- Photon Emitted
- Electron falls DOWN
- ΔE is Negative

The Emission Spectrum Signature of Hydrogen



The Spectral Series Matrix

Series Name	Target State	Drops from	Region	Energy Change
Lyman Series	$n_f = 1$	$n \geq 2$	Ultraviolet (UV)	Massive
Balmer Series	$n_f = 2$	$n \geq 3$	Visible Light	Medium
Paschen Series	$n_f = 3$	$n \geq 4$	Infrared (IR)	Small

Mr. Mohamad's Problem-Solving Framework



Step 1: Analyze & Sketch

Identify knowns and unknowns.

Sketch the energy levels.
Draw the transition arrow
(up for absorption, down for emission).



Step 2: The Math Engine

Calculate individual energy levels: $E_n = -13.6/n^2$

Find the difference:

$$\Delta E = E_f - E_i$$

If finding wavelength, use the shortcut:

$$\lambda = (1240 \text{ eV}\cdot\text{nm}) / \Delta E$$



Step 3: The Reality Check

Evaluate your answer.
Are units in eV or nm?

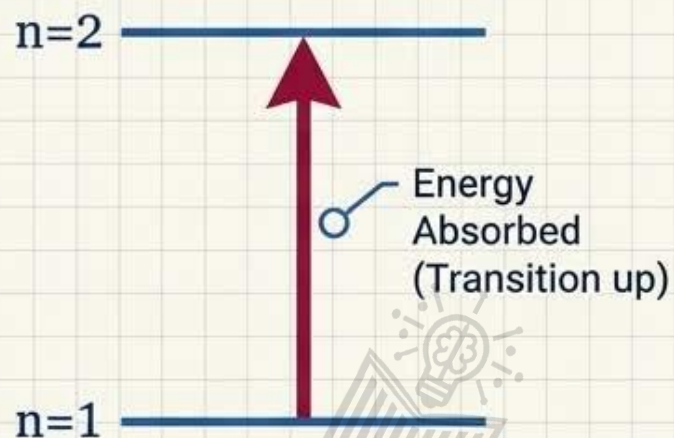
Is the sign correct?
(Negative = energy released/photon emitted)

Is the electromagnetic region realistic?

Master Example 1: Calculating Energy Jumps

The Problem: An electron moves from the lowest energy level ($n=1$) to the second level ($n=2$). Determine the energy absorbed.

Analyze & Sketch



The Math Engine



$$E_1 = -13.6 \text{ eV} \times \frac{1}{1^2} = -13.6 \text{ eV}$$

$$E_2 = -13.6 \text{ eV} \times \frac{1}{2^2} = -3.40 \text{ eV}$$

$$\Delta E = E_f - E_i$$

$$\Delta E = -3.40 \text{ eV} - (-13.6 \text{ eV})$$

$$\Delta E = \underline{\underline{+10.2 \text{ eV}}}$$

The Reality Check



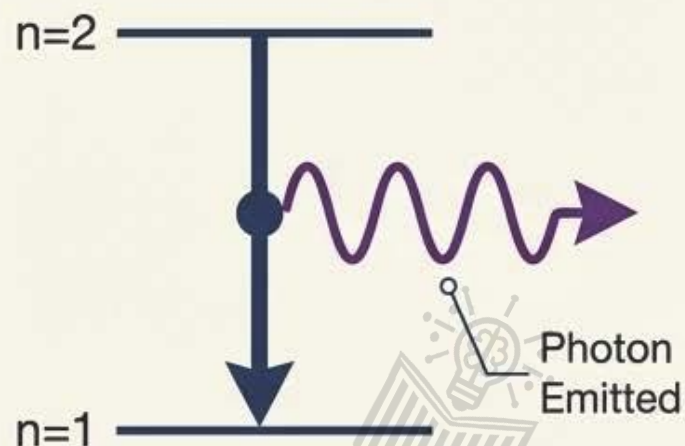
Sign is positive (+) → Energy is absorbed.

Magnitude (~10 eV) matches the massive gap between $n=1$ and $n=2$.

Master Example 2: Emitted Photon Wavelengths

The Problem: An excited electron drops from $n=2$ to $n=1$. Calculate the energy and wavelength of the emitted photon.

Analyze & Sketch



The Math Engine

$$\Delta E = E_1 - E_2$$

$$\Delta E = -13.6 \text{ eV} - (-3.40 \text{ eV}) = -10.2 \text{ eV}$$

(Energy is emitted)

Using the shortcut: $c = \lambda f$ and $E = hf$

$$\lambda = \frac{hc}{\Delta E}$$

$$\lambda = \frac{1240 \text{ eV} \cdot \text{nm}}{10.2 \text{ eV}}$$

$$\lambda = 122 \text{ nm}$$

The Reality Check



The sign of ΔE is negative (emission).

The wavelength is 122 nm, which falls correctly into the Ultraviolet range (Lyman series target $n=1$).

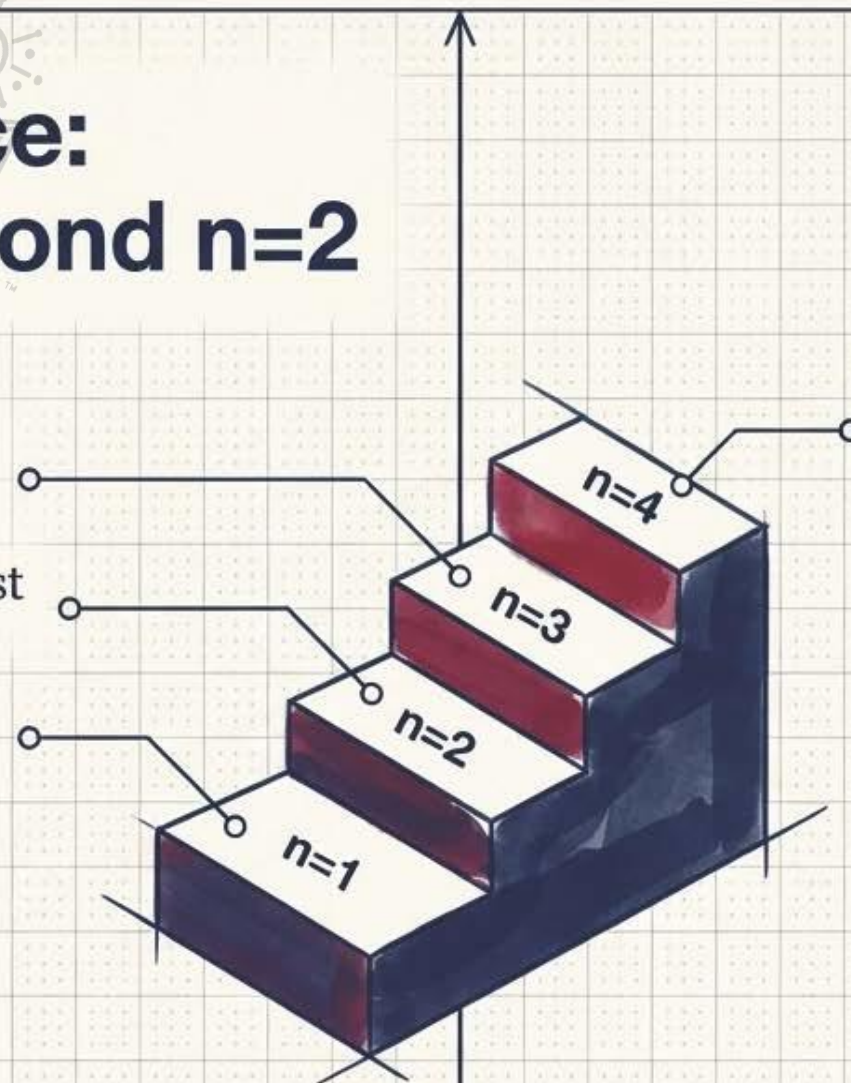
Applied Practice: Expanding Beyond n=2

Pre-Calculating Higher States

To solve complex transitions, first map the higher energy levels:

$$E_3 = -13.6 \text{ eV} \times (1/3^2) \\ = -1.51 \text{ eV}$$

$$E_4 = -13.6 \text{ eV} \times (1/4^2) \\ = -0.85 \text{ eV}$$



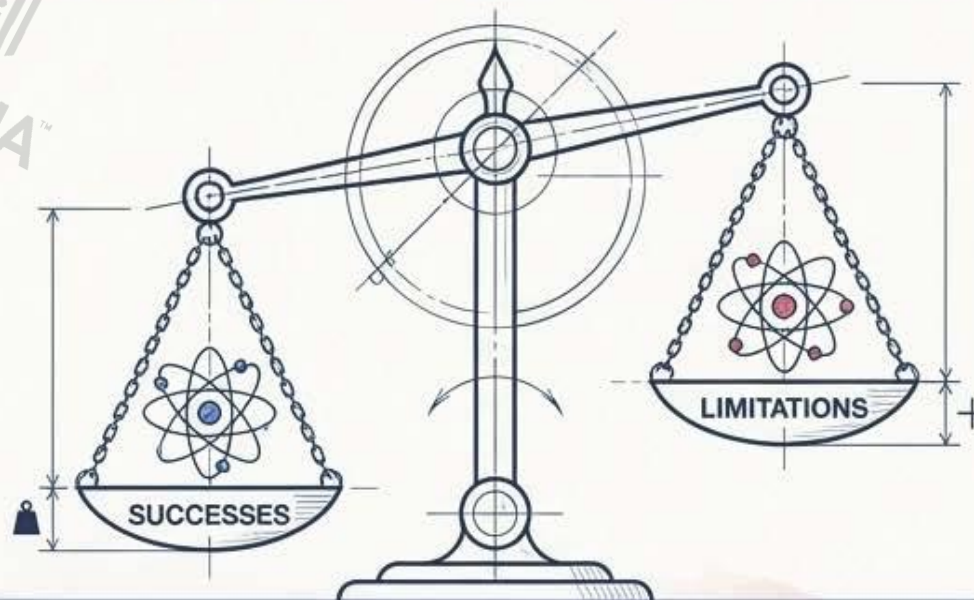
Executing a Complex Transition

Calculate the energy difference for a drop from n=3 to n=2.

$$\Delta E = E_3 - E_2 \\ \Delta E = -1.51 \text{ eV} - (-3.40 \text{ eV}) \\ \Delta E = 1.89 \text{ eV}$$

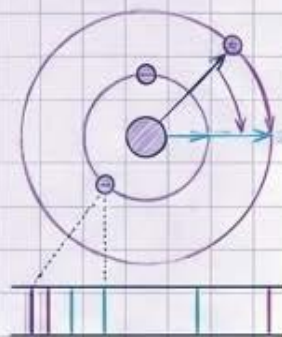
**Result: Balmer Series
Visible Emission**

The Legacy of the Bohr Model: Successes and Limitations



Triumphs of the Model

- **Perfectly** predicted the emission spectrum and wavelengths of Hydrogen.
- **Calculated** ionization energy that perfectly matched experimental data.
- **Successfully** introduced the concept of quantized energy states.



Where the Physics Breaks Down

- **The Neon Challenge:** Failed to predict behavior for any multi-electron atom (the math falls apart due to electron-electron repulsion).
- **The "Why" Problem:** Bohr could not explain why the laws of electromagnetism (which cause spiraling) should suddenly stop working inside the atom.



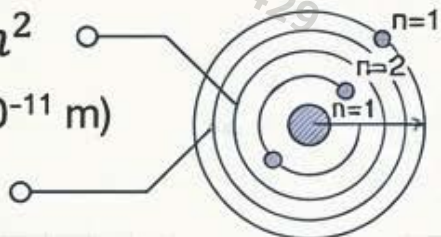
The Master Formula Cheat Sheet

The Quantum Dashboard

Physical Structure (Radius)

$$r_n = r_1 \times n^2$$

$$(r_1 = 5.3 \times 10^{-11} \text{ m})$$



Energetic Structure (Energy Levels)

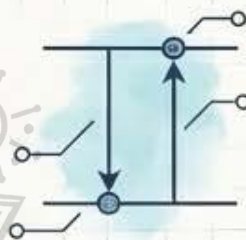
$$E_n = -13.6 \text{ eV} \times \left(\frac{1}{n^2} \right)$$

n = 3	=====	n = 1 - 3.40 eV
n = 2	=====	n = 2 - -1.51 eV
n = 1	=====	n = 1 - 13.6 eV

Transitions (The Golden Rule)

$$\Delta E = E_f - E_i$$

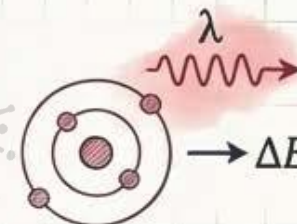
(Negative = Emission,
Positive = Absorption)



The Photon Link (Light)

$$E_{\text{photon}} = \Delta E_{\text{atom}}$$

$$\lambda = \frac{1240 \text{ eV} \cdot \text{nm}}{\Delta E}$$



Constants Footer: Planck's constant $h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$ | Speed of light $c = 3.0 \times 10^8 \text{ m/s}$ | $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

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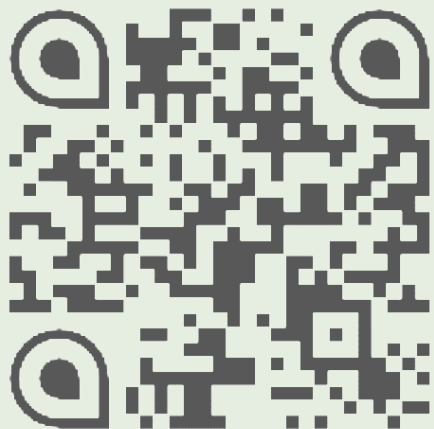
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A Stepping Stone to the Quantum Universe

The Bohr model paved the way for modern quantum mechanics, fundamentally changing our understanding of chemistry, chemical reactions, and the architecture of the cosmos.

Prepared by Mr. Mohamad

Wishing you outstanding success in your
physics studies!



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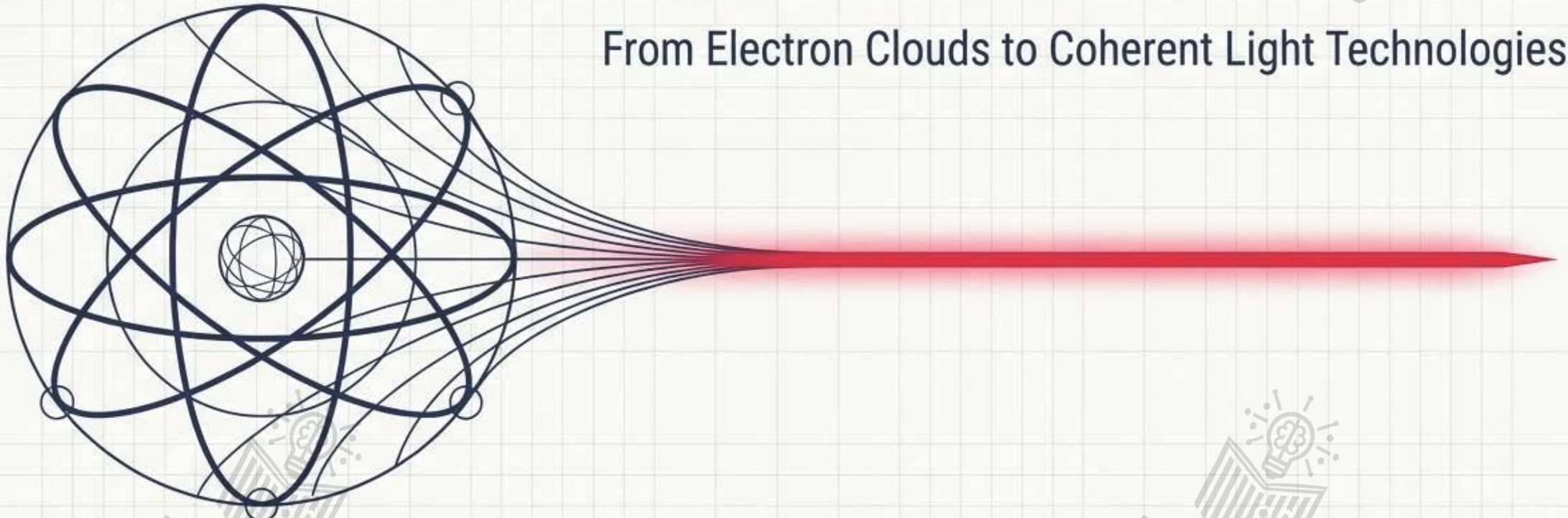
Module (22): Quantum Theory and the Atom

04

Fourth Lesson:
The Quantum Model
of the Atom

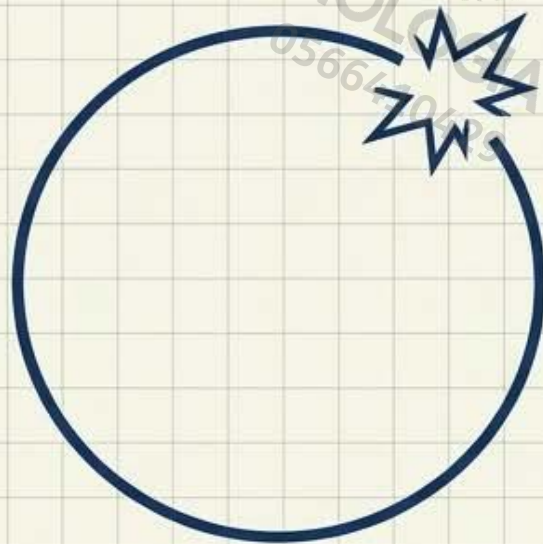
QUANTUM MODELS & LASERS: THE MASTER GUIDE

From Electron Clouds to Coherent Light Technologies



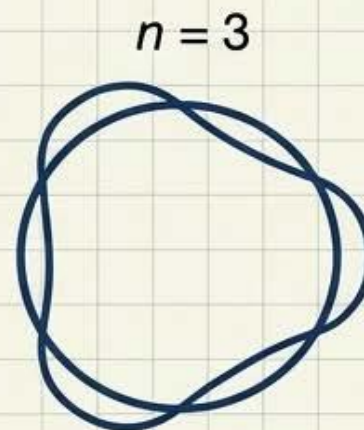
Presented by Mr. Mohamad

The Problem: Bohr's Limitation

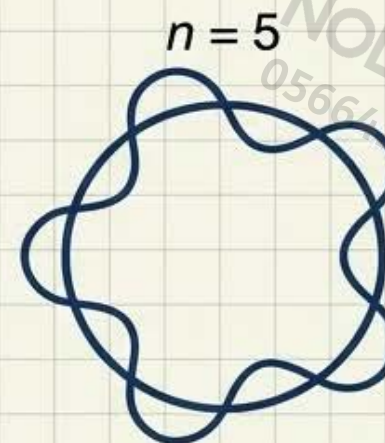


Bohr's quantized orbits failed to predict electron energies for atoms with more than one electron.

The Solution: de Broglie Waves



Stable condition:
closed loop



Stable condition:
closed loop



Unstable condition:
disconnected ends

Particles have wave properties:
momentum mv , wavelength $\lambda = \frac{h}{mv}$
Angular momentum condition: $mvr = \frac{nh}{2\pi}$
Therefore: $\frac{hr}{\lambda} = \frac{nh}{2\pi} \rightarrow 2\pi r = n\lambda$

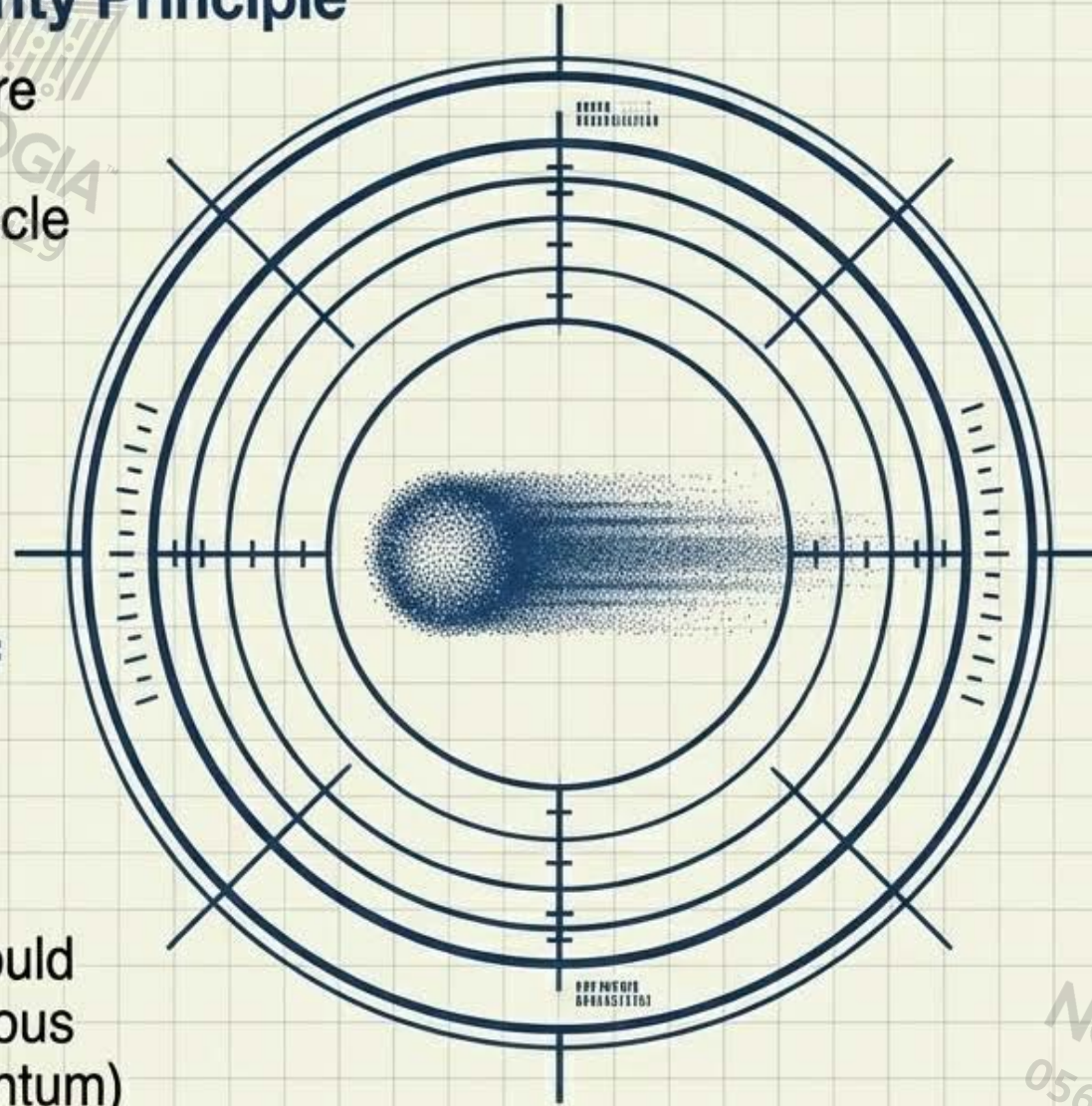
Takeaway: Stable electron orbits must have a circumference equal to a whole-number multiple (n) of de Broglie wavelengths.

Heisenberg Uncertainty Principle

It is impossible to measure exactly both the position and momentum of a particle at the same time. You can only know them approximately.

Critical Thinking Proof

If an electron cloud were reduced to the size of a nucleus, the immense certainty of its position would require adding a tremendous amount of energy (momentum) to satisfy the equation.

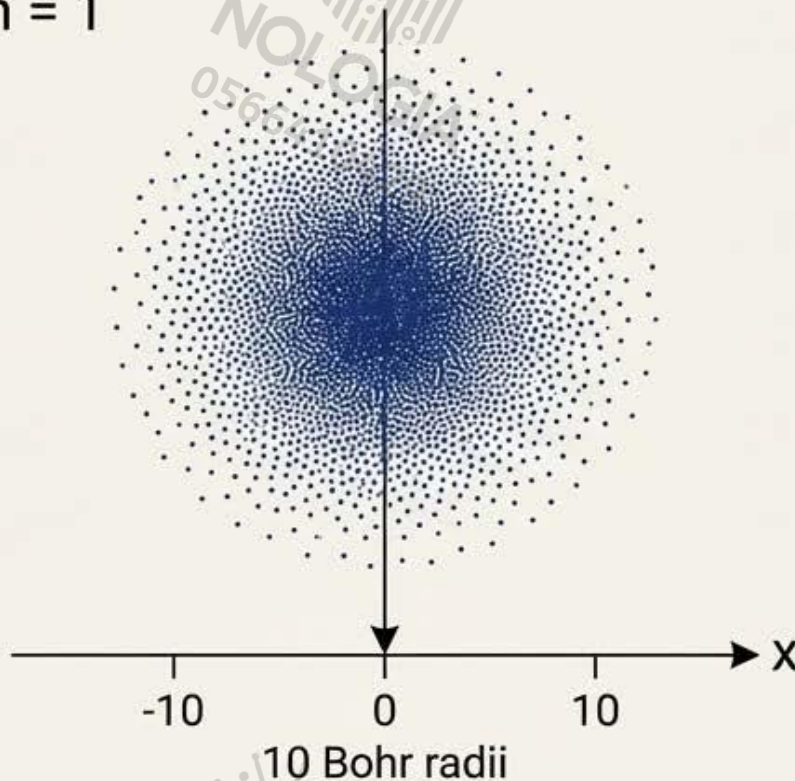


The Paradigm Shift

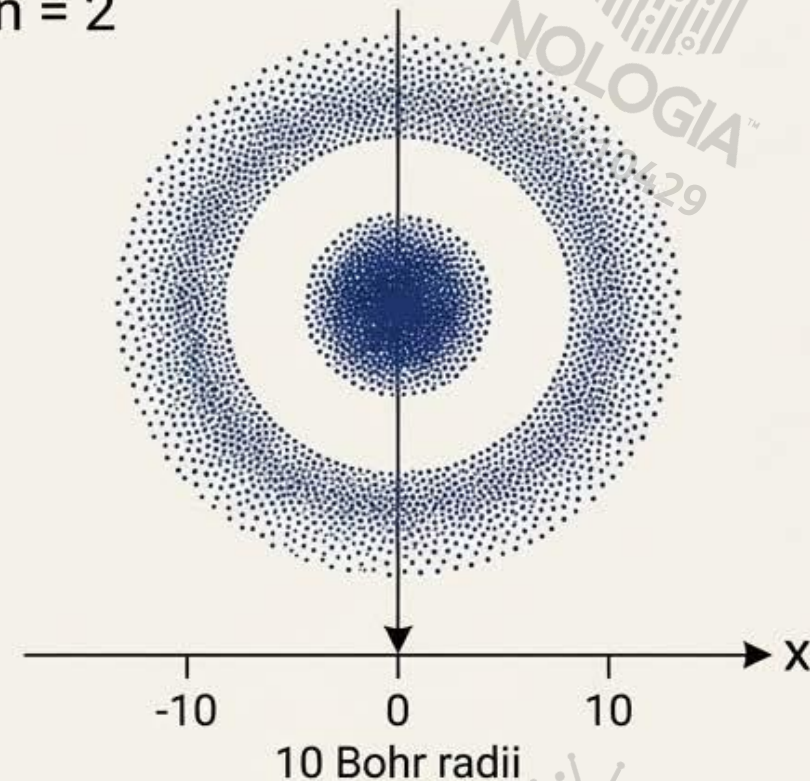
Physics moves from absolute tracking of rigid orbits to predicting only the probability of an electron's specific location.

Probability Cloud Density Maps

$n = 1$



$n = 2$



Defining the Cloud

The three-dimensional region in which there is a high probability of finding the electron.

Density = Probability

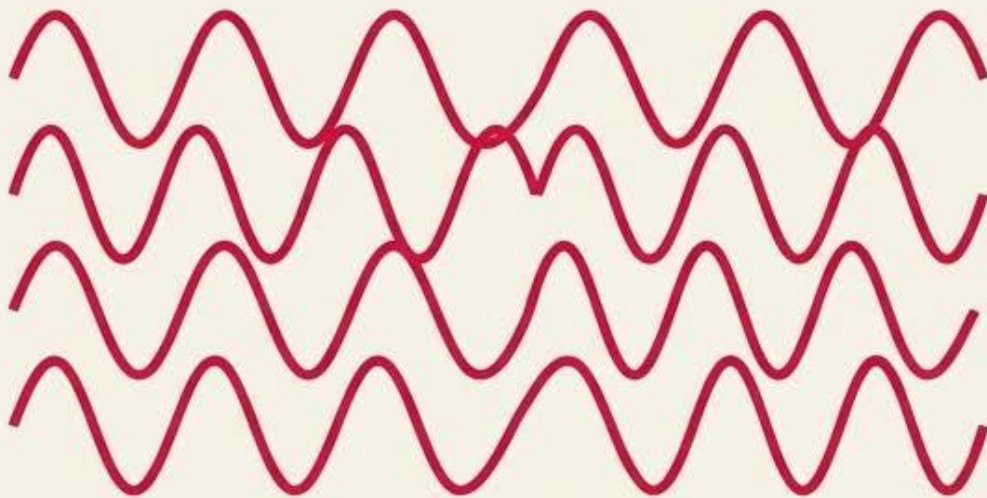
The visual density of the dots corresponds directly to the mathematical likelihood of finding the electron in that specific location.

Link to Bohr

The modern quantum model predicts that the most probable distance for a electron equals the exact radius predicted by the older Bohr model.

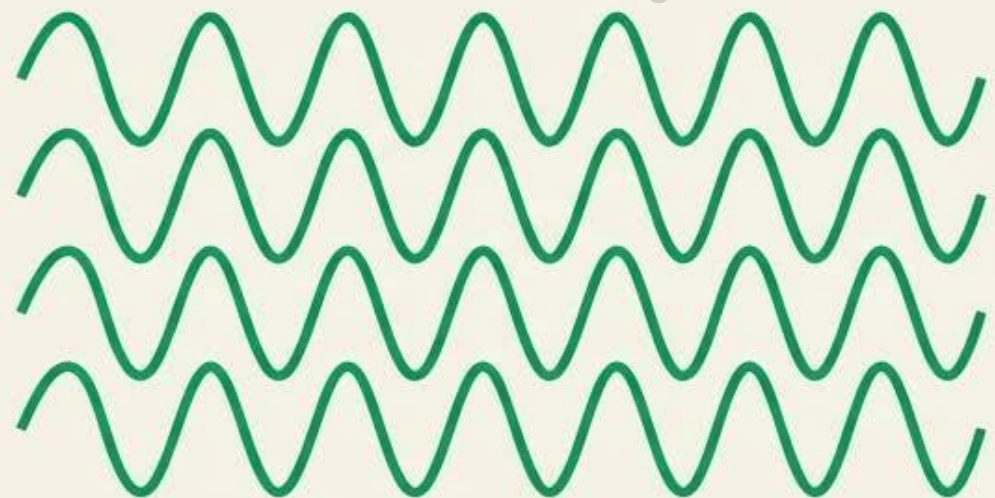
The Light Spectrum Matrix

Incoherent Light



- Continuum of many different wavelengths
- Waves travel in all directions
- Out of phase (not at the same point in their cycle)
- Example: Standard incandescent lightbulb

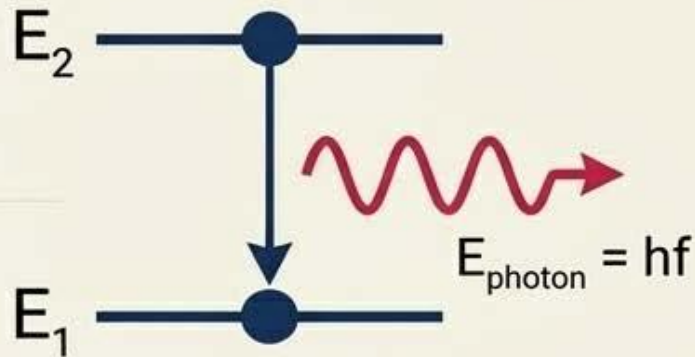
Coherent Light (Lasers)



- Monochromatic (one identical wavelength and frequency)
- Unidirectional (highly directional, narrow beam)
- In phase (peaks and troughs perfectly aligned in time)
- Example: Laser devices

The Emission Engine Matrix

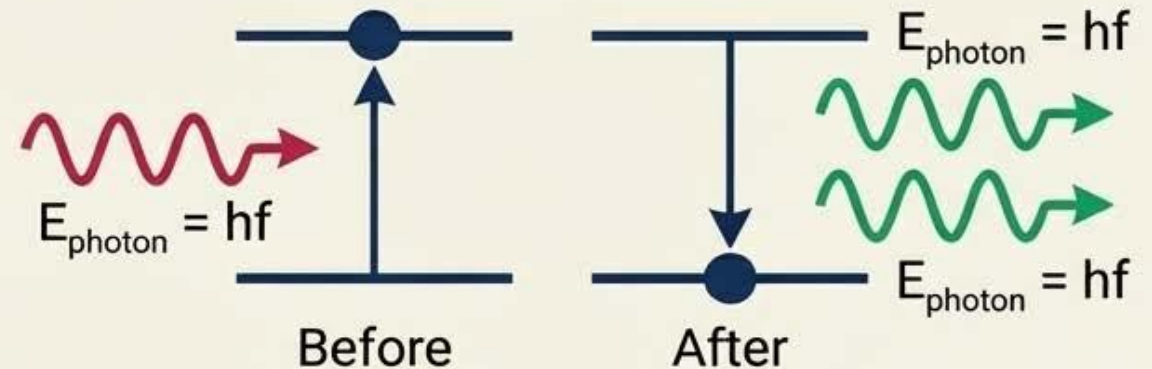
Spontaneous Emission



Excited atom returns to ground state naturally. Emits one photon.

$$\text{Energy: } E_{\text{photon}} = hf = E_2 - E_1$$

Stimulated Emission (Einstein, 1917)

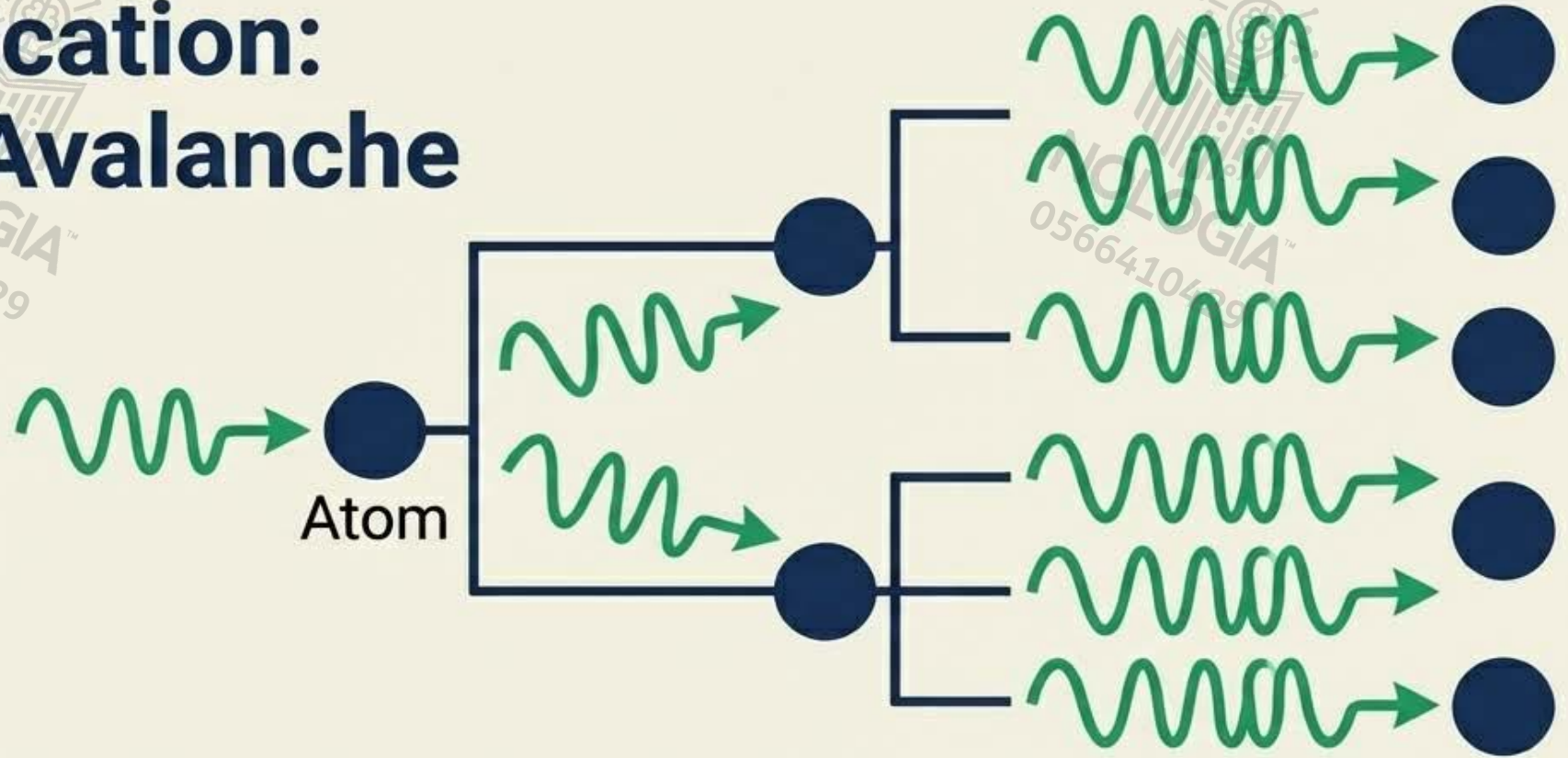


Photon with exact energy difference strikes an already excited atom.

Result: Original photon is unaffected. Atom emits a second photon. Both are identical in frequency, wavelength, and phase.

Light Amplification: The Photon Avalanche

L - Light
A - Amplification by
S - Stimulated
E - Emission of
R - Radiation



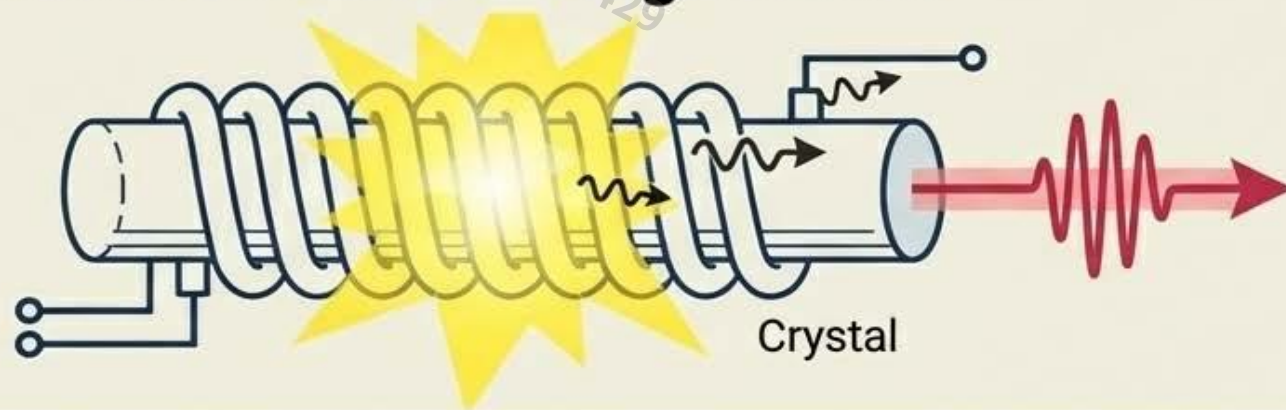
The 3 Strict Conditions for Lasing

1. Atoms must be in an excited state (Pumped).
2. Atoms must remain excited long enough to be struck by a passing photon.
3. Photons must be physically contained so they can strike other atoms.

Fulfilling Condition #1: Atom Excitation (Pumping)

The process of forcing atoms into higher energy states to prepare for stimulated emission.

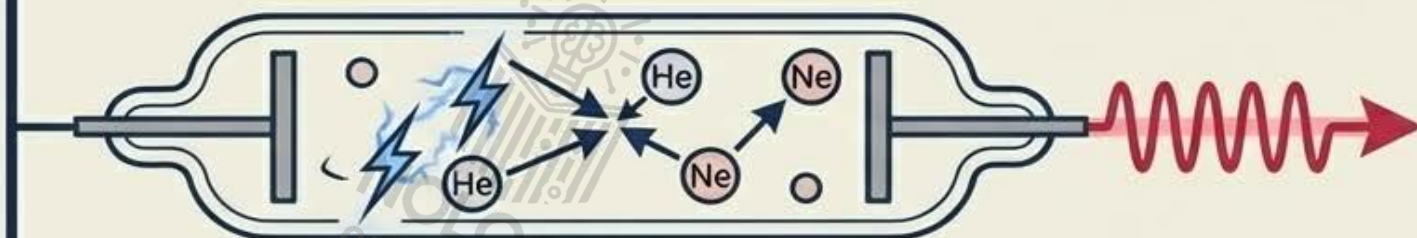
Method 1: Intense Light Flash



A higher-energy (shorter wavelength) light is absorbed by the active medium. When it decays, it triggers a **brief, high-power pulse** of laser light.

Note: Green light can pump a red laser, but red cannot pump a green laser due to lower energy levels.

Method 2: Electrical Collision



An electric discharge excites atoms. Excited helium atoms physically collide with neon atoms, pumping them to an excited state.

Results in a continuous beam rather than pulses.

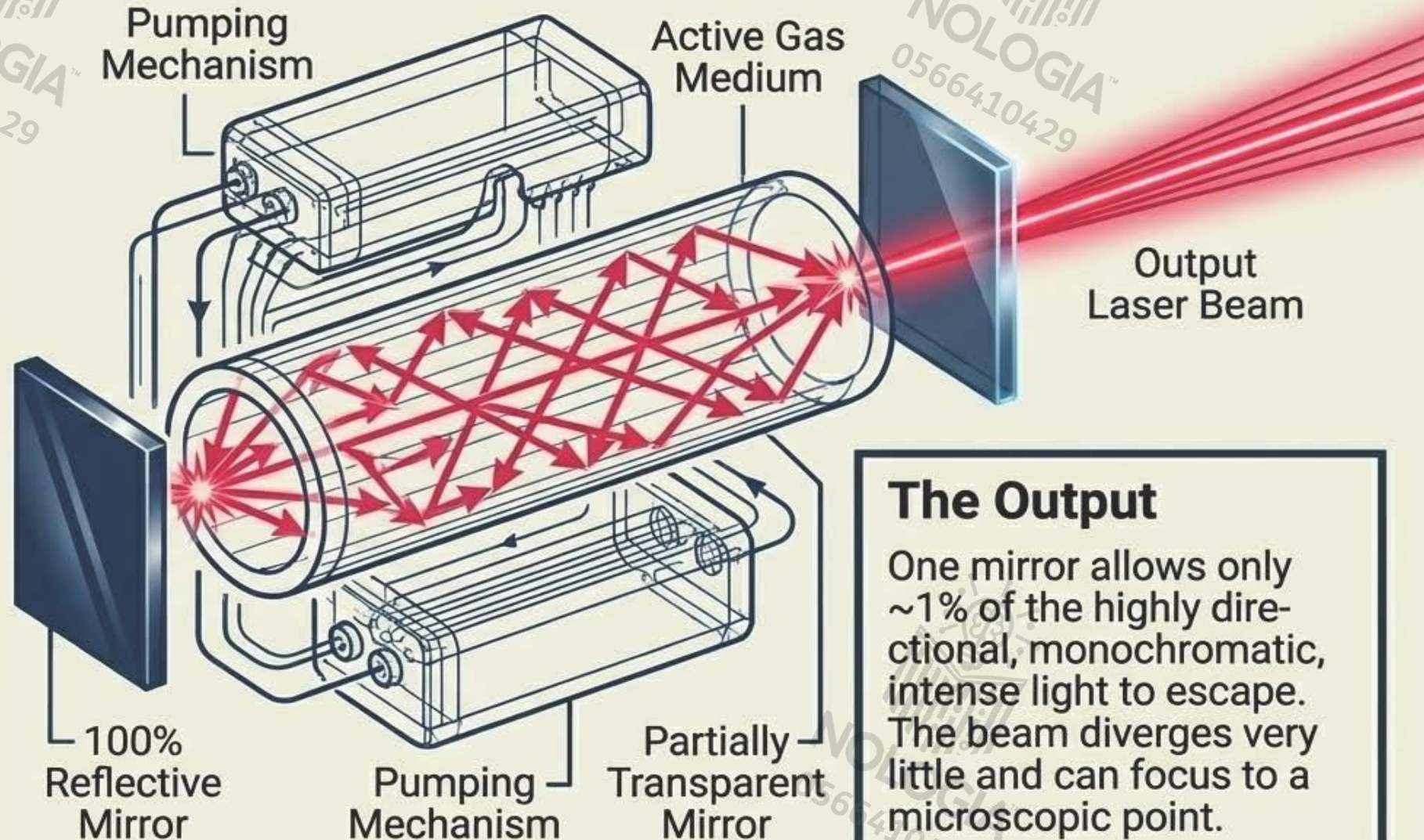
The Anatomy of a Laser: Synthesis Matrix

The Chamber

Contains the lasing atoms and the emitted photons in a controlled vacuum or crystal matrix.

The Mirrors (Feedback Loop)

Parallel mirrors trap photons, forcing them to bounce back and forth, striking more atoms and releasing more photons in a continuous avalanche.



The Output

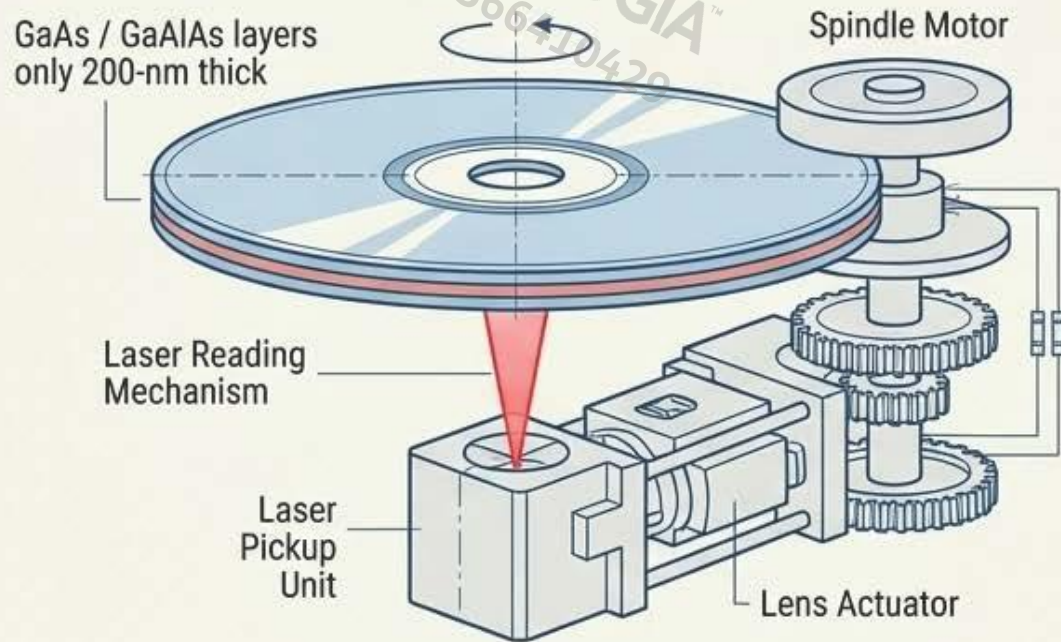
One mirror allows only ~1% of the highly directional, monochromatic, intense light to escape. The beam diverges very little and can focus to a microscopic point.

The Example Compendium: Master Application Matrix

Technology / Application	Key Laser Trait	Operational Purpose
Laser Pointers	Narrow & Directional	Highlighting specific targets over distances with minimal beam spread.
Fiber-Optic Communications	Total Internal Reflection	Rapidly switching pulses on/off to transmit phone and computer data globally with minimal signal loss.
Optical Media (CD/DVD/Blu-ray)	Monochromatic / Short Wavelength (λ)	Precision reading of microscopic, high-density data pits carved into semiconducting solid layers.
Laser Printers	Precision Focus (760 nm)	Scanning over a drum to alter electrostatic charges, forming exact images for toner adhesion.
Lunar Surveying & Topography	Low Divergence / Time-of-Flight	Bouncing off mirrors on the Moon to measure Earth-Moon distances and map topography to within 10 cm accuracy.

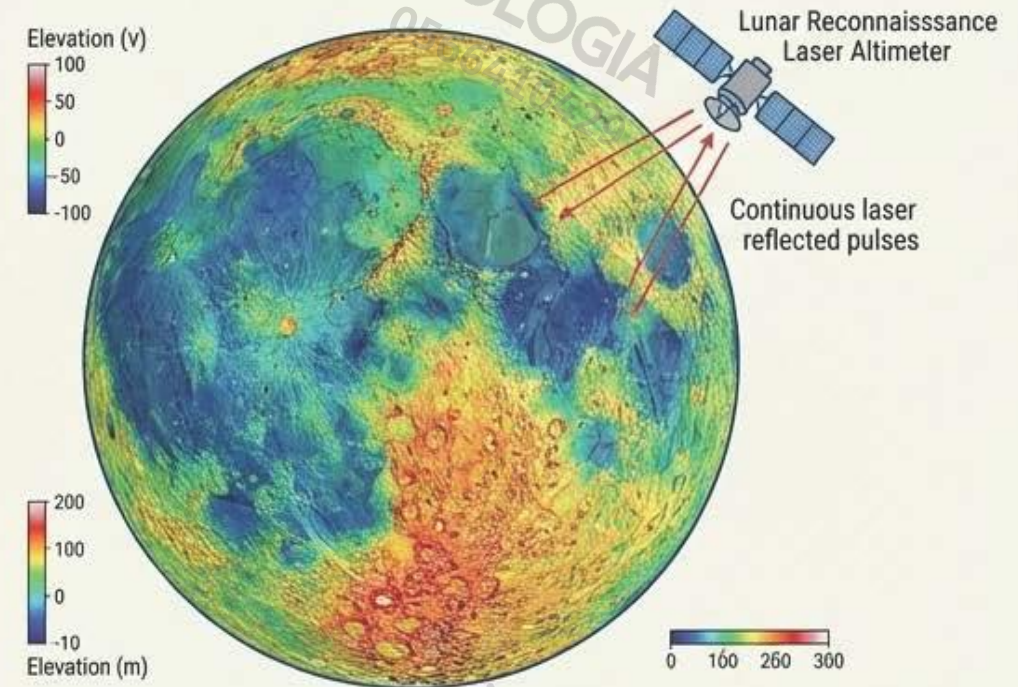
Deep Dive: Optical Storage & Space Topography

Consumer Tech: Optical Storage



- Constructed from semiconducting solids (GaAs / GaAlAs layers only 200-nm thick).
- The Wavelength Rule: Shorter wavelength = smaller focus spots = higher data density.
- Blu-ray uses a much shorter wavelength than a standard 650 nm DVD laser, allowing it to store 5x more data in the exact same physical footprint.

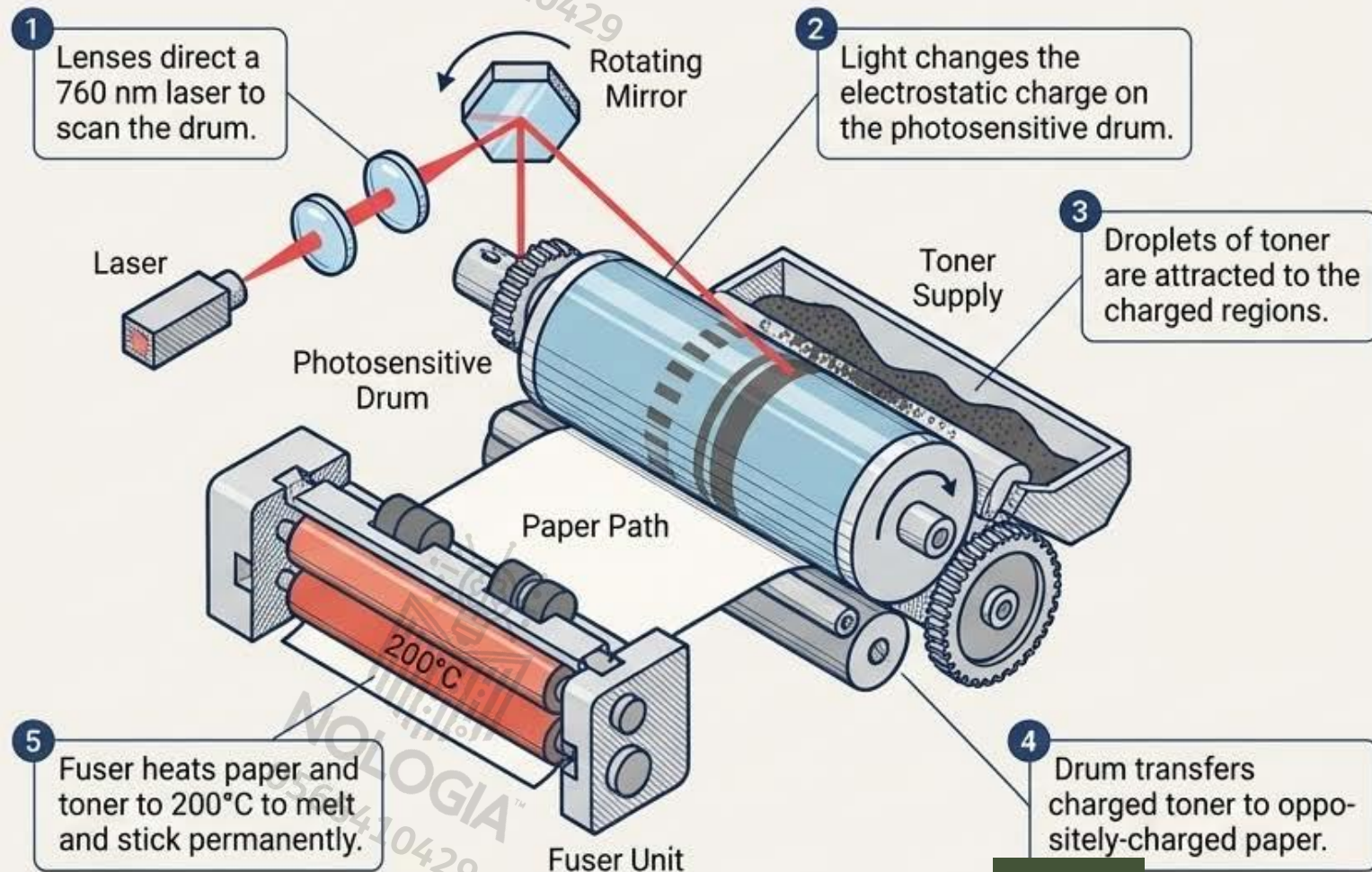
Research: Lunar Surveying



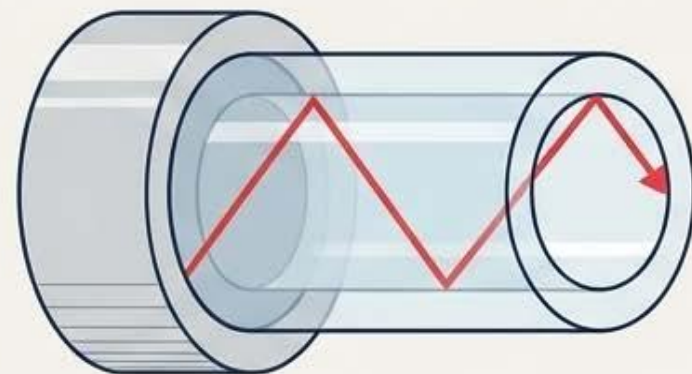
- The Lunar Reconnaissance Orbiter fires continuous laser pulses at the lunar surface.
- By measuring the time required for light to bounce back, scientists produce topographical maps accurate to within 10 cm.
- Crucial for tracking tectonic plate movement and selecting safe landing sites for future manned missions.

Deep Dive: Data Transmission & Printing

Laser Printing Mechanics



Fiber-Optic Communications



Lasers rapidly switch on and off, transmitting digital pulses.

Utilizes total internal reflection to keep light contained.

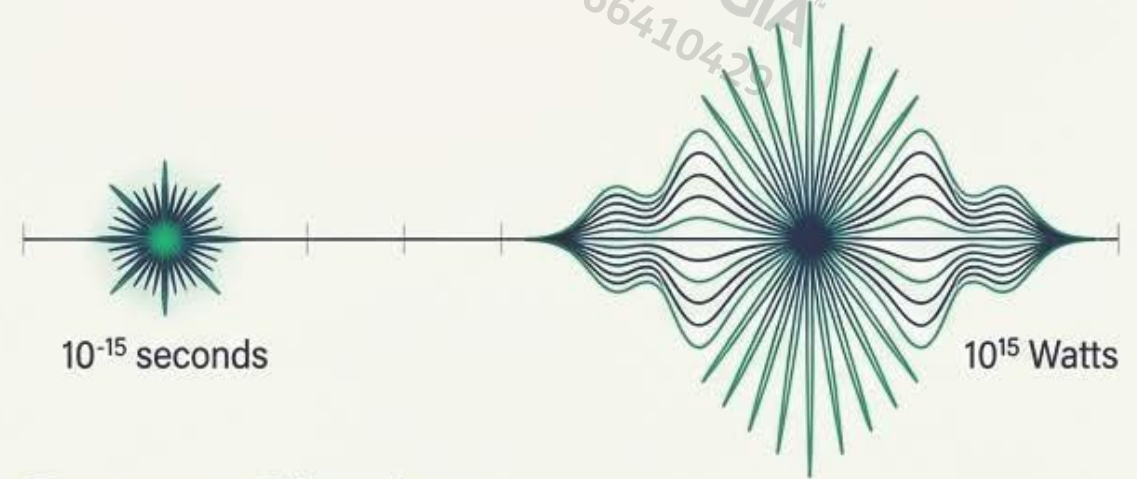
Replaces heavy copper wire for global telephone, television, and computer data networks.

Deep Dive: Medicine & Extreme Physics



Healthcare & Dental Diagnostics

- **Diagnostics:** Infrared sensors measure reflected heat and light waves to map hidden decay below the hard enamel without dangerous X-rays.
- **Reversing Decay:** Lasers stimulate reactions that activate stem cells, promoting the formation of new dentin in the tooth's core.
- **Dermatology:** Used under medical supervision to precisely target and remove spider veins, unwanted hair, and tattoos.



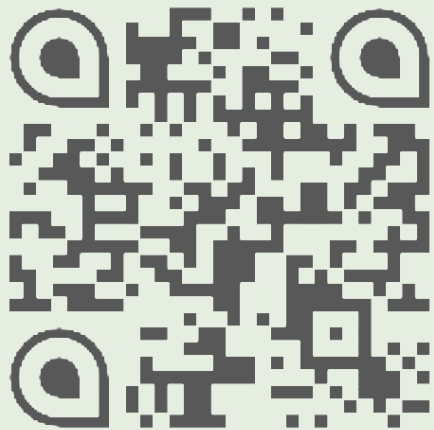
Extreme Physics

- **Ultrafast Lasers:** Emit bursts as brief as 10^{-15} seconds, acting as microscopic strobe lights to investigate incredibly fast changes in atomic structures.
- **Ultra-powerful Lasers:** Generate massive pulses reaching petawatt (10^{15} watts) power levels, used to create high-temperature plasmas for advanced energy production research.

Module (24): Nuclear and Particle Physics

	Lesson Title	Page
24-1	The Nucleus	92
24-2	Nuclear Decay and Reactions	107

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Module (24): Nuclear and Particle Physics

01

First Lesson: The Nucleus

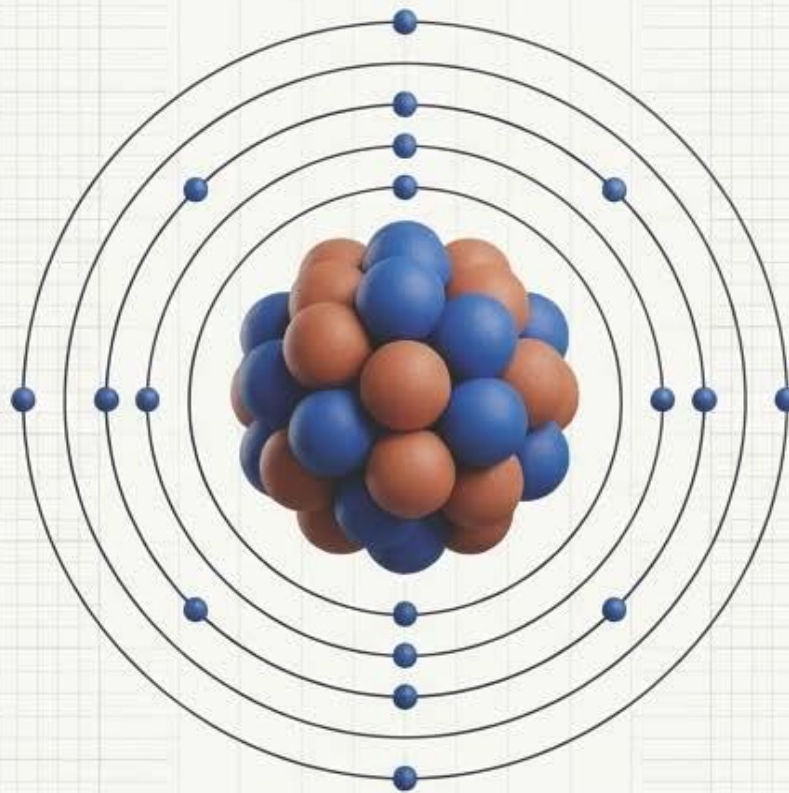


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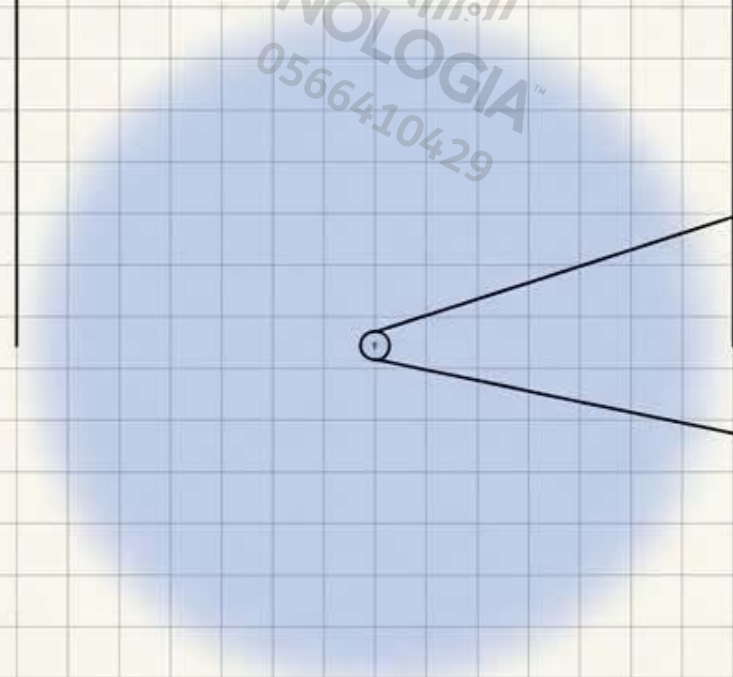
The Nucleus: Comprehensive Master Guide

Anatomy, Nuclear Forces, and the Mathematics of Binding Energy

Curated specifically for
the academic mastery of
Mr. Mohamad.

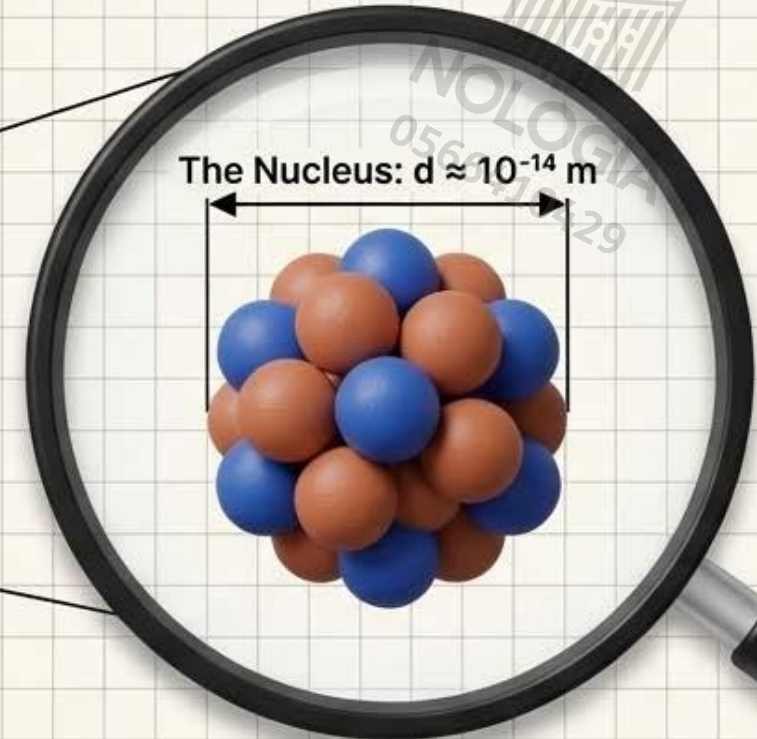
The Atomic Scale: Vast Space vs. Infinite Density

The Atom: $d \approx 10^{-10}$ m



Rutherford's gold foil experiment revealed that the atom is mostly empty space, with a positively charged core.

The Nucleus: $d \approx 10^{-14}$ m



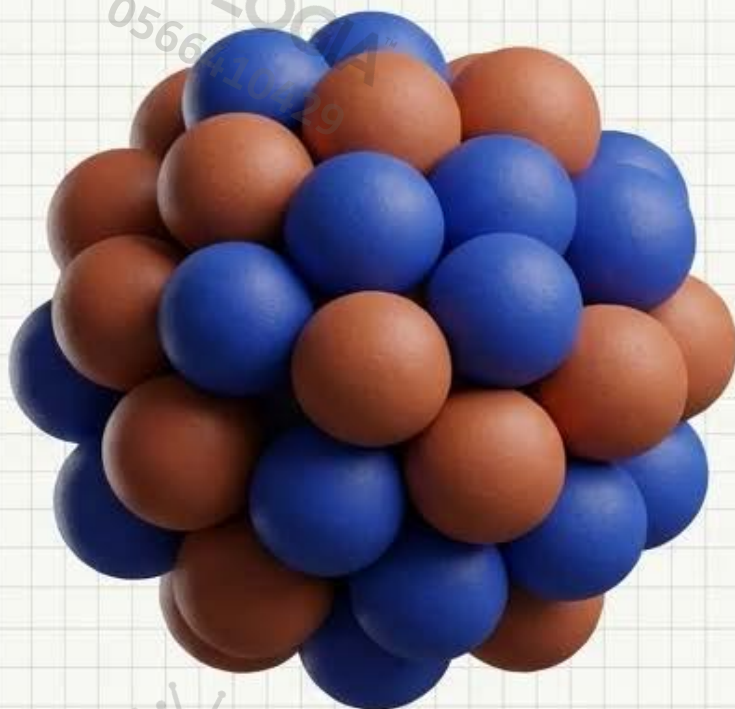
The radius of an atom is 10,000 times larger than its nucleus.

The Density Paradox

The nucleus occupies proportionally less space in an atom than the Sun does in our solar system. Its density is an incomprehensible $1.4 \times 10^{18} \text{ kg/m}^3$.

Mind-Blowing Fact: If a nucleus were just 1 cm^3 , it would weigh about 1 billion tons (90,000 times more massive than the largest ocean liner).

Anatomy of the Core: The Nucleons



Nucleons

The collective foundational term used to describe both protons and neutrons within the core.

Atomic Number (Z)

The exact number of protons. This uniquely determines the element's identity and its total positive charge ($+Ze$).

Mass Number (A)

The total combined number of nucleons (Protons + Neutrons). The approximate nuclear mass is $\cong A \times u$.

The Standard Metric for Mass

1 Atomic Mass Unit (u) $\approx 1.66 \times 10^{-27}$ kg

This is roughly the mass of 1 isolated proton or neutron, and is equivalent to the mass of approximately 1800 electrons.

Isotopes & The Spectrometer Proof

Definition of an Isotope

Atoms belonging to the exact same element (identical number of protons) but possessing different masses due to a varying number of neutrons.

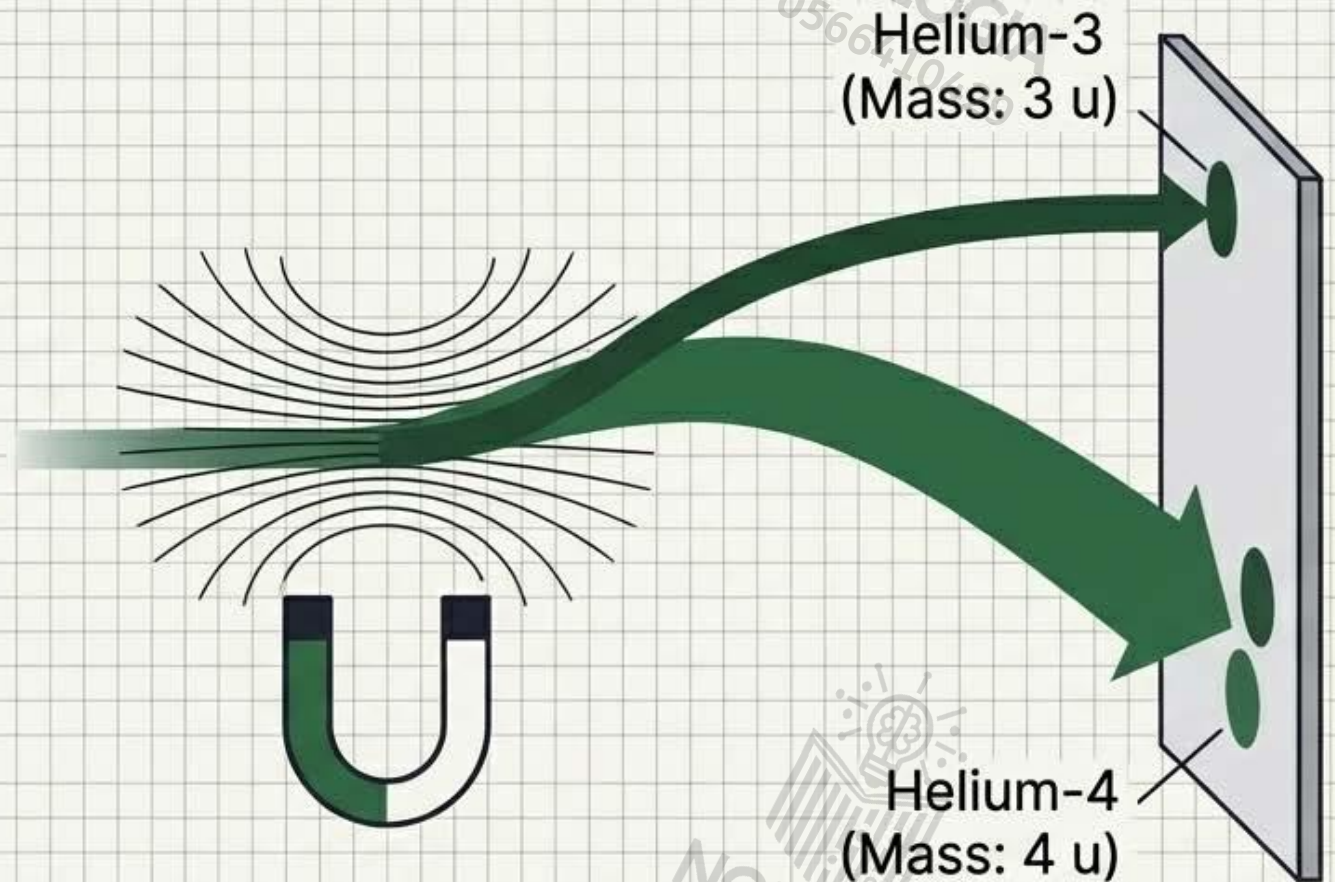
Standard Notation: Large element symbol X , superscript A (Mass Number), subscript Z (Atomic Number).

The Mass Spectrometer Proof

Mass spectrometers physically separate elements by mass using electromagnetism.

When analyzing a pure helium sample, the detector registers two distinct landing spots.

This proves that neutral helium exists in two varying weights.

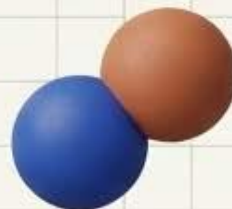


The Isotope Gallery: Visualizing Variations

Hydrogen Isotopes



Protium (${}^1_1\text{H}$) | 1 p, 0 n



Deuterium (${}^2_1\text{H}$) | 1 p, 1 n



Tritium (${}^3_1\text{H}$) | 1 p, 2 n

Helium Isotopes



Helium-3 (${}^3_2\text{He}$) | 2 p, 1 n



Helium-4 (${}^4_2\text{He}$) | 2 p, 2 n

Key Rule: Despite having different physical masses, all isotopes of an element contain the **exact same number of electrons**. Therefore, they behave **chemically identical** to one another.

Average Atomic Mass: The Real-World Mixture

The Puzzle: If individual nucleons weigh ~ 1 u, why does Chlorine have a mass of 35.453 u on the periodic table instead of a whole number?

Chlorine-35
(Abundant)



Chlorine-37
(Rare)



The Answer: Weighted Averages

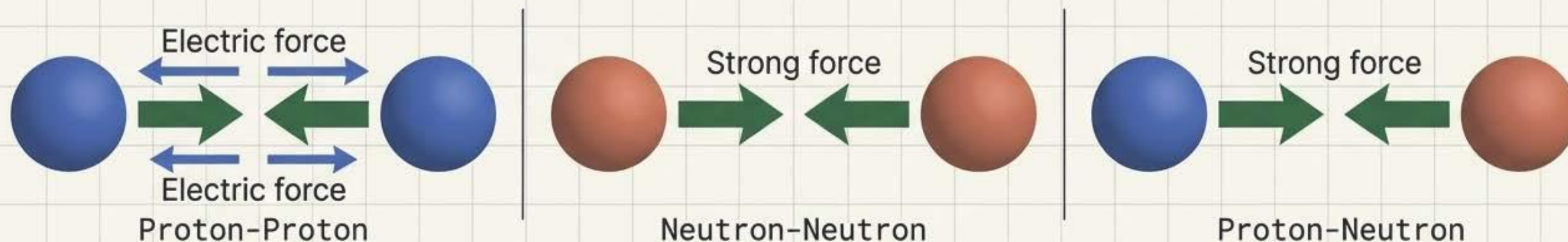
Elements exist in nature not as a single type of atom, but as a mixture of different isotopes. The mass recorded on the periodic table is a calculated **weighted average** of these naturally occurring forms based on their abundance.

The Universal Anchor

To standardise all atomic weights globally, modern physics defines 1 atomic mass unit (1 u) as being exactly $1/12$ the mass of a single Carbon-12 isotope.

The Great Tug-of-War: Strong Nuclear Force

The Paradox: Protons are positively charged. According to the laws of electromagnetism, they should violently repel each other and tear the nucleus apart. Why doesn't this happen?



The Resolution

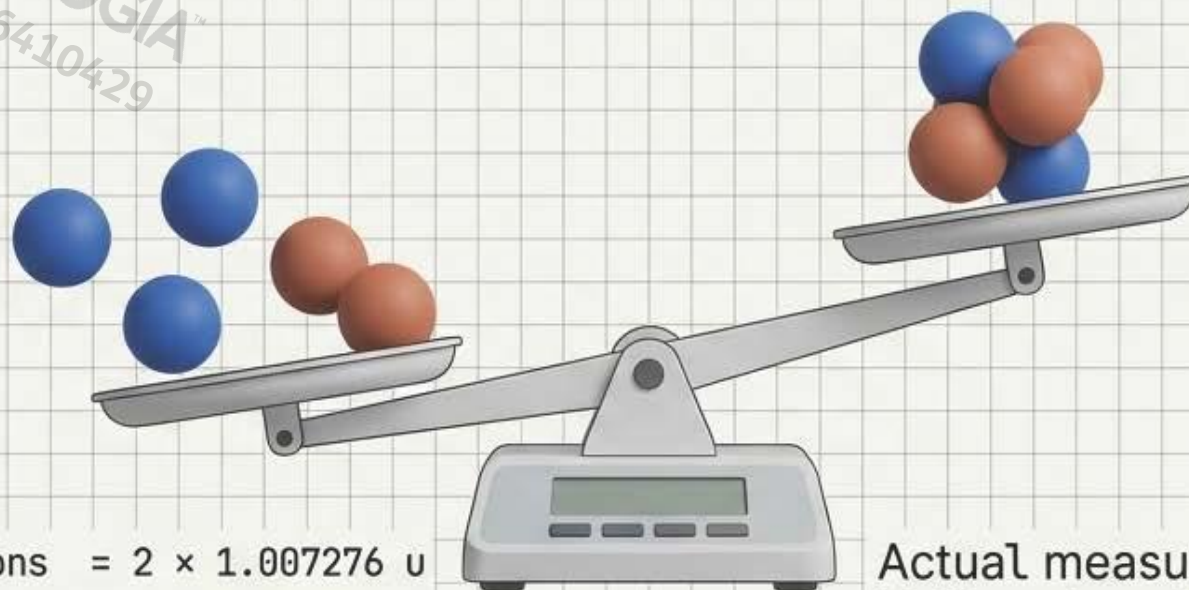
The Strong Nuclear Force is an attractive force operating between ALL adjacent nucleons, holding the core together.

Critical Properties

Strength: It is over 100 times stronger than electromagnetic repulsion.

Range: It is incredibly short-range. It only functions when nucleons are within roughly a proton's radius (1.4×10^{-15} m).

The Mystery of the Missing Mass (Mass Defect)



Mass of 2 isolated protons = $2 \times 1.007276 \text{ u}$

Mass of 2 isolated neutrons = $2 \times 1.008665 \text{ u}$

Expected Total Mass = 4.031882 u

Actual measured mass of
Helium-4 nucleus:

= 4.002603 u

The Mass Defect = $4.031882 \text{ u} - 4.002603 \text{ u} = 0.029279 \text{ u}$

Observation: The actual mass of an assembled nucleus is always LESS than the sum of its individual parts. Where did the 0.029279 u go?

Binding Energy & The Einstein Conversion

The Answer to the Missing Mass

The missing mass (mass defect) was converted entirely into Binding Energy—the energy required to overcome the strong force and pull the nucleus apart. Binding energy is always expressed as a negative value because the assembled nucleus has less energy than separated nucleons.

Applying $E = mc^2$

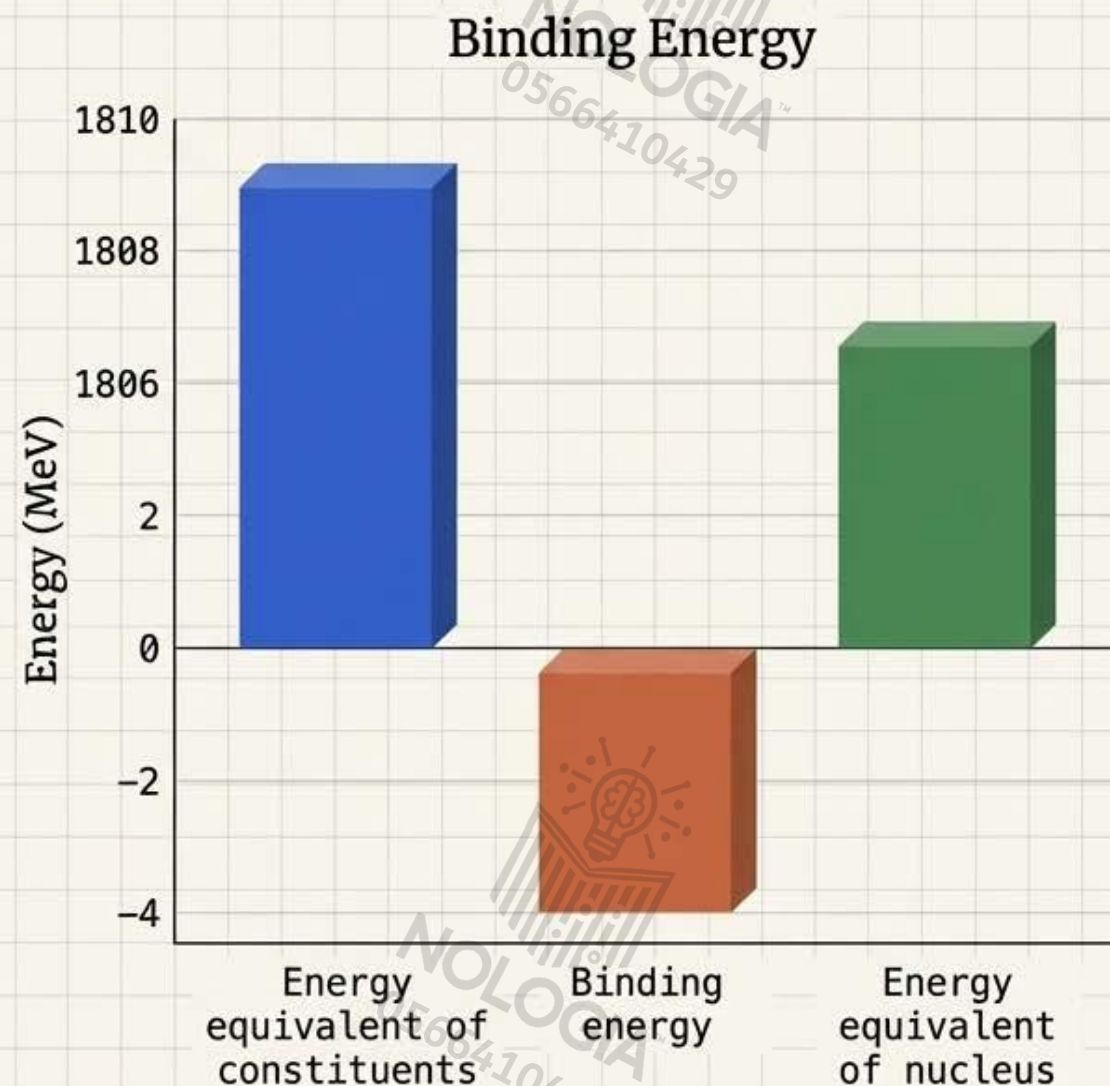
$$\begin{aligned} \text{Energy} &= (1.6605 \times 10^{-27} \text{ kg}) \times (2.9979 \times 10^8 \text{ m/s})^2 \\ \text{Energy} &= 1.4924 \times 10^{-10} \text{ Joules} \end{aligned}$$

Converting Joules to Electron Volts (eV)

$$\begin{aligned} E &= (1.4924 \times 10^{-10} \text{ J}) \times (1 \text{ eV} / 1.60218 \times 10^{-19} \text{ J}) \\ E &= 931.49 \times 10^6 \text{ eV} = 931.49 \text{ MeV} \end{aligned}$$

THE MASTER CONSTANT

1 u of mass defect = 931.49 MeV of binding energy.



Master Algorithm: Tritium Binding Energy (Step 1)

Target Acquisition

Target Nucleus: Tritium (${}^3_1\text{H}$)



Given mass of Tritium isotope = 3.016049 u

Parts Inventory Ledger

1	Hydrogen Atom (1 proton + 1 electron)	=	1.007825 u
2	Neutrons ($2 \times 1.008665 \text{ u}$)	= +	2.017330 u
Total mass of independent parts		=	3.025155 u

CRITICAL PRO-TIP FOR EXAMS:

Notice we use the mass of a full Hydrogen atom (1.007825 u) instead of an isolated proton (1.007276 u).

Why? Because this automatically accounts for the mass of the atom's electron, ensuring perfect accuracy when calculating the mass defect of the whole isotope!

Master Algorithm: Tritium Binding Energy (Steps 2 & 3)

Step 2: Calculate Mass Defect

Formula: Mass Defect = Assembled Mass - Total Parts Mass

mass of tritium:	3.016049 u
- mass of tritium's parts:	3.025155 u
<u>mass defect:</u>	-0.009106 u



Step 3: Convert to Binding Energy

Formula: $E = (\text{mass defect in u}) \times (\text{energy equivalent of 1 u})$

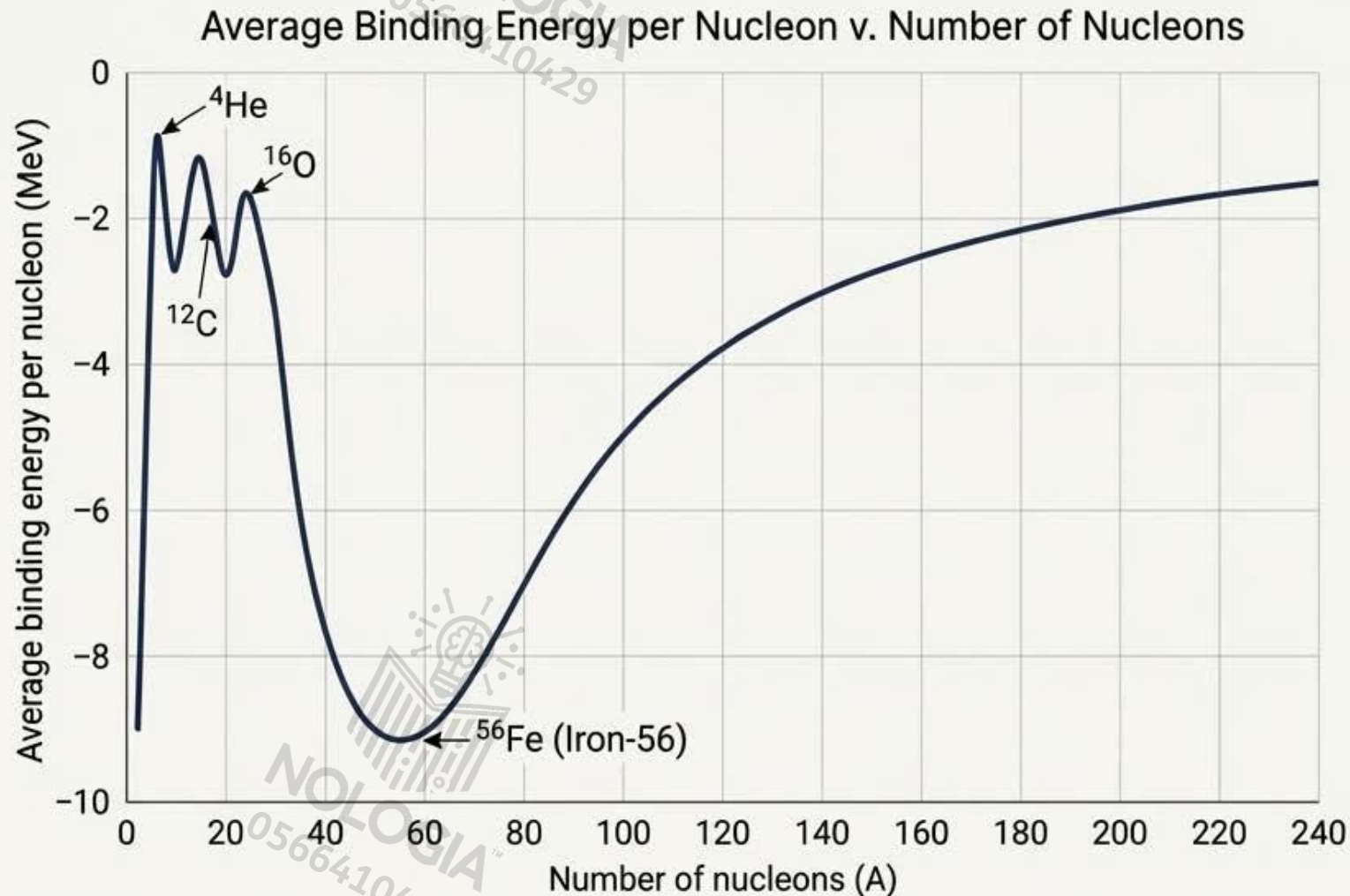
$$E = (-0.009106 \text{ u}) \times (931.49 \text{ MeV/u})$$

$$E = -8.4821 \text{ MeV}$$

Evaluate the Answer:

- ✓ Are units correct? Mass in u, Energy in MeV.
- ✓ Does the sign make sense? Yes, binding energy must be negative.
- ✓ Is the magnitude realistic? Yes, binding energy per nucleon $(-8.4821 / 3) \approx -2.8 \text{ MeV}$, which matches standard stability curves for light elements.

The Stability Curve: The Reign of Iron-56



The Metric of Stability

Nuclear stability is measured by binding energy per nucleon. A more negative value indicates a more tightly bound and stable nucleus.

The King of Stability

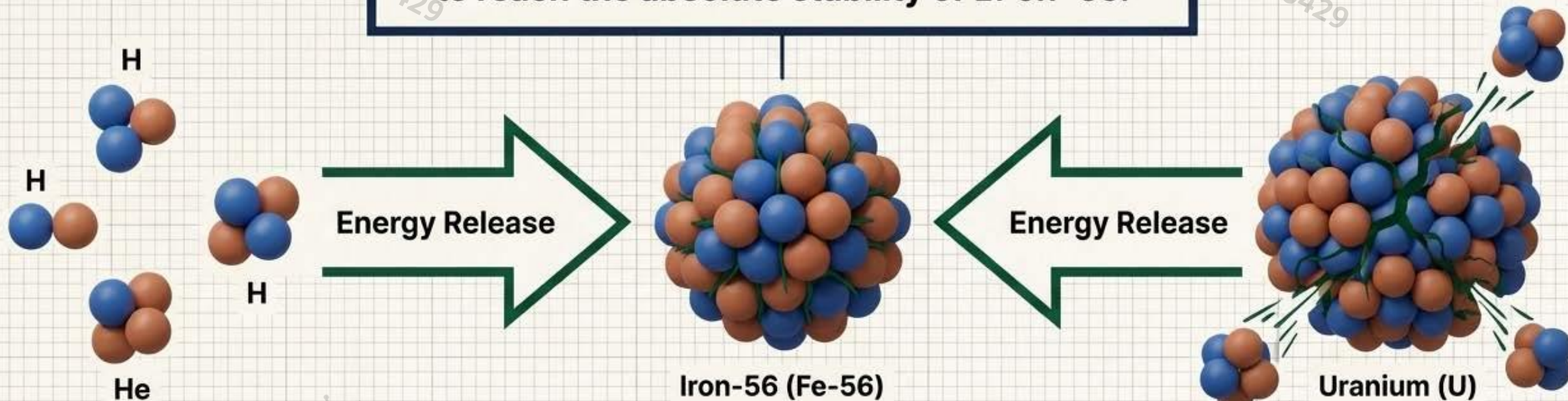
Iron-56 ($^{56}_{26}\text{Fe}$) has the greatest magnitude of binding energy per nucleon. It sits at the lowest point of the curve, making it the most stable isotope in the known universe.

The Curve Dynamics

Light elements drop steeply down into the Iron-56 valley. Heavy massive elements gradually climb out of the valley as electromagnetic repulsion begins to fight the strong force.

The Universal Drive for Stability: Fusion and Fission

The Universal Rule: All nuclei inherently "want" to reach the absolute stability of Iron-56.



Nuclear Fusion

Small nuclei (approaching $A=56$) become more stable by fusing together. Under extreme temperatures (like inside stellar cores), nuclei smaller than Iron fuse into larger, more tightly bound nuclei, releasing massive energy.

Nuclear Fission & Decay

Large nuclei ($A > 56$) are less strongly bound because electromagnetic repulsion between the many protons begins to overcome the short-range strong nuclear force. Nuclei with $Z > 92$ readily decay or split into smaller, more stable pieces.

Module Mastery Sheet // Comprehensive Summary

Prepared exclusively for the final exam review of Mr. Mohamad.

Key Variables

A = Mass Number
(Protons + Neutrons)

Z = Atomic Number
(Protons)

Nucleon = Any particle in the core (p or n)

Isotope = Same Z, different A

$$1 \text{ u} \approx 1.6605 \times 10^{-27} \text{ kg}$$

Master Formulas

Calculating Mass Defect:

$$\text{Mass Defect} = (\text{Assembled Nucleus Mass}) - (\text{Sum of Parts Mass})$$

***Reminder:** Always use the mass of a full Hydrogen atom for the proton parts to account for the electron mass.*

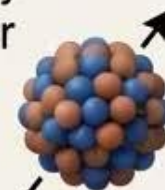
Calculating Binding Energy:

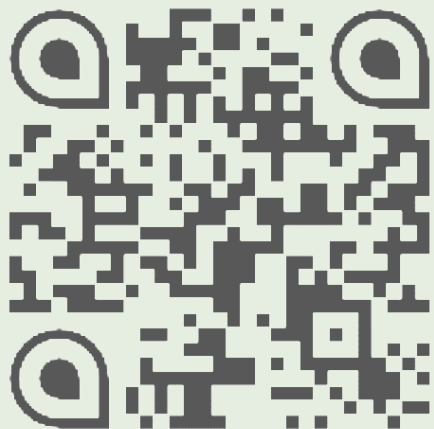
$$\text{Binding Energy} = \text{Mass Defect} \times 931.49 \text{ MeV/u}$$

***Reminder:** Binding energy is **always negative**.

Core Axioms

1. The Strong Nuclear Force is >100x stronger than EM repulsion, but only works at extremely short distances ($\sim 10^{-15} \text{ m}$).
2. The actual mass of a nucleus is always less than the sum of its isolated parts. The missing mass becomes **binding energy**.
3. Maximum nuclear stability occurs at Iron-56. Smaller atoms fuse to reach it; larger atoms undergo fission/decay to reach it.





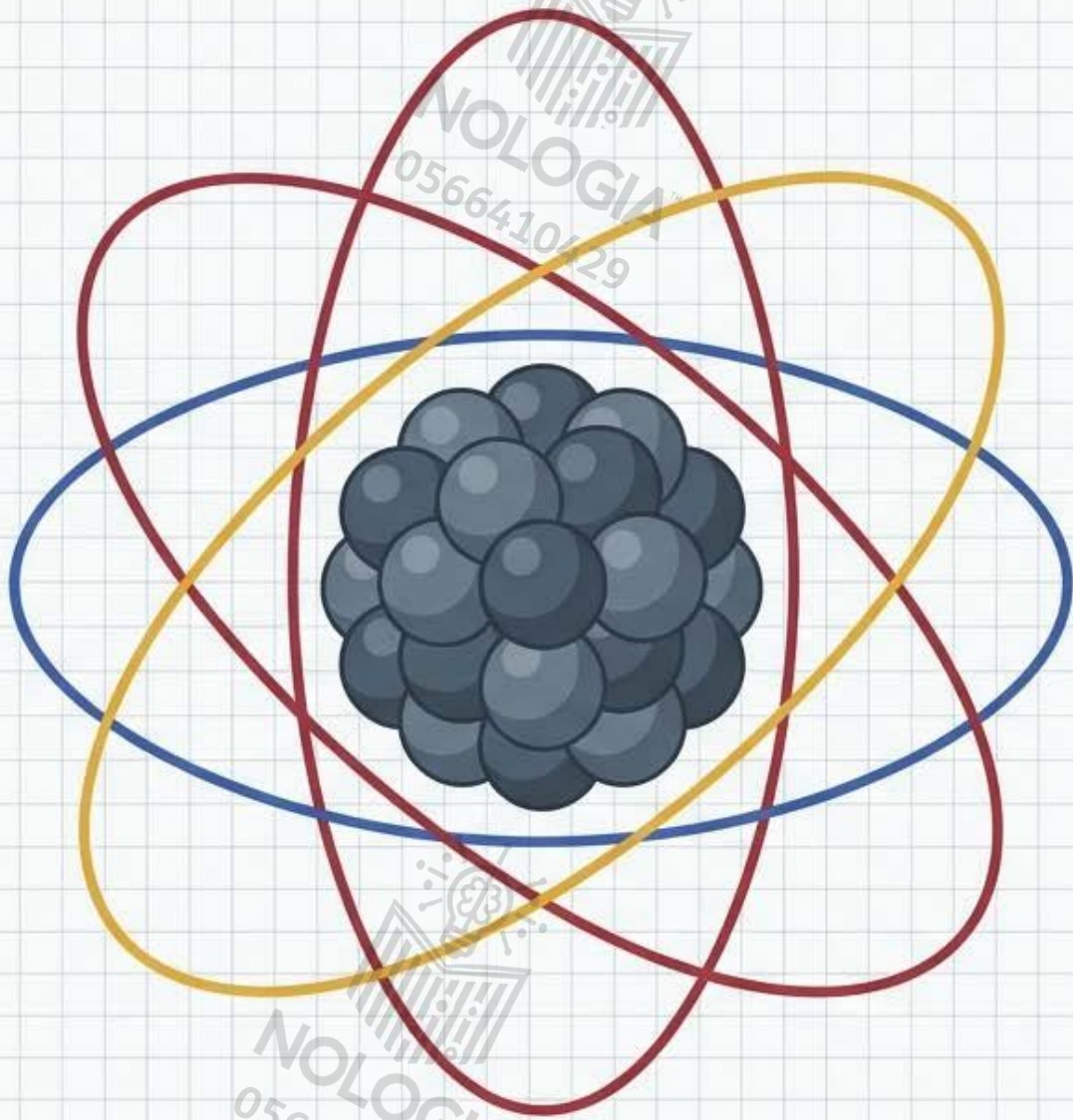
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Module (24): Nuclear and Particle Physics

02

Second Lesson:
Nuclear Decay and Reactions



Mr. Mohamad's Masterclass: Nuclear Decay & Reactions

A Complete Visual Guide to
Transmutation, Equations, and Half-Life

Target Audience:

Grade 12 Advanced Physics

Objective:

Comprehensive mastery of nuclear mechanics with step-by-step guided examples.

Historical Context

1896

Henri Becquerel discovers radiation via fogged photographic plates exposed to uranium.

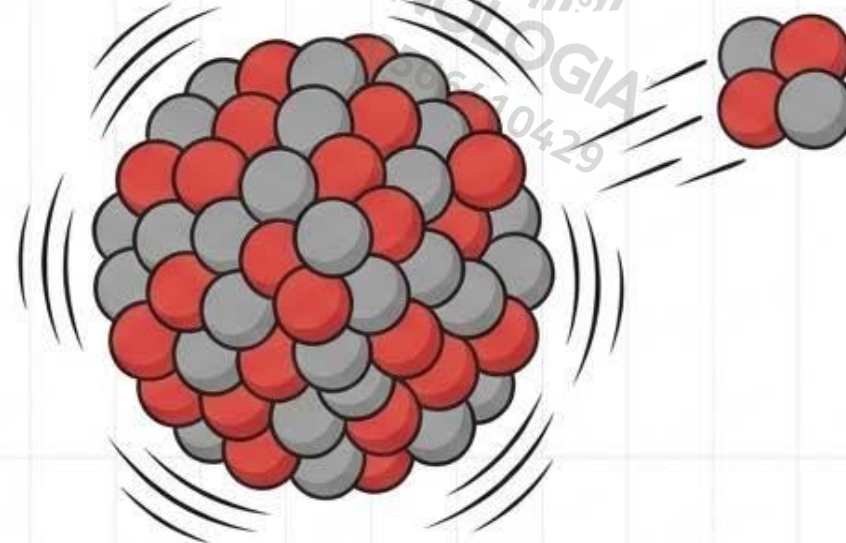
1909

Ernest Rutherford identifies alpha particles as helium-4 nuclei.



Medical imaging technology shows how quickly fundamental physics led to real-world applications.

The Mechanism of Instability



Radioactive Decay

Nuclei that emit particles and energy are *radioactive*. This is a natural process driven by a single fundamental goal: unstable nuclei decay to become more stable.

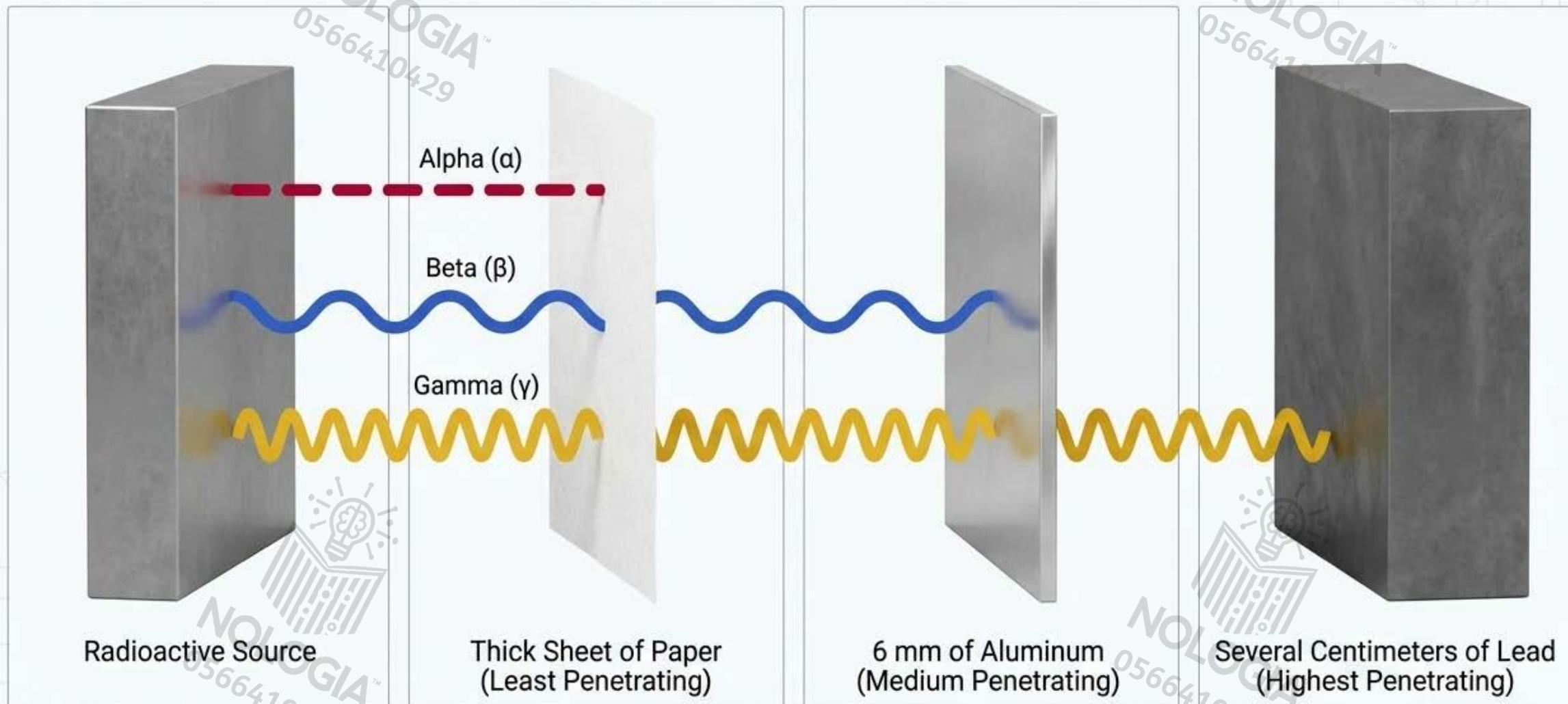
The Radiation Trinity Matrix

	Alpha Decay	Beta Decay	Gamma Decay
Identity	Helium Nucleus	Electron / Positron	High-Energy Photon
Charge	+2	-1	No Charge
Transmutes Mass (A)	$A \rightarrow A - 4$	$A \rightarrow A$	$A \rightarrow A$
Transmutes Atomic Number (Z)	$Z \rightarrow Z - 2$	$Z \rightarrow Z + 1$	$Z \rightarrow Z$
Transmutes Neutrons (N)	$N \rightarrow N - 2$	$N \rightarrow N - 1$	$N \rightarrow N$

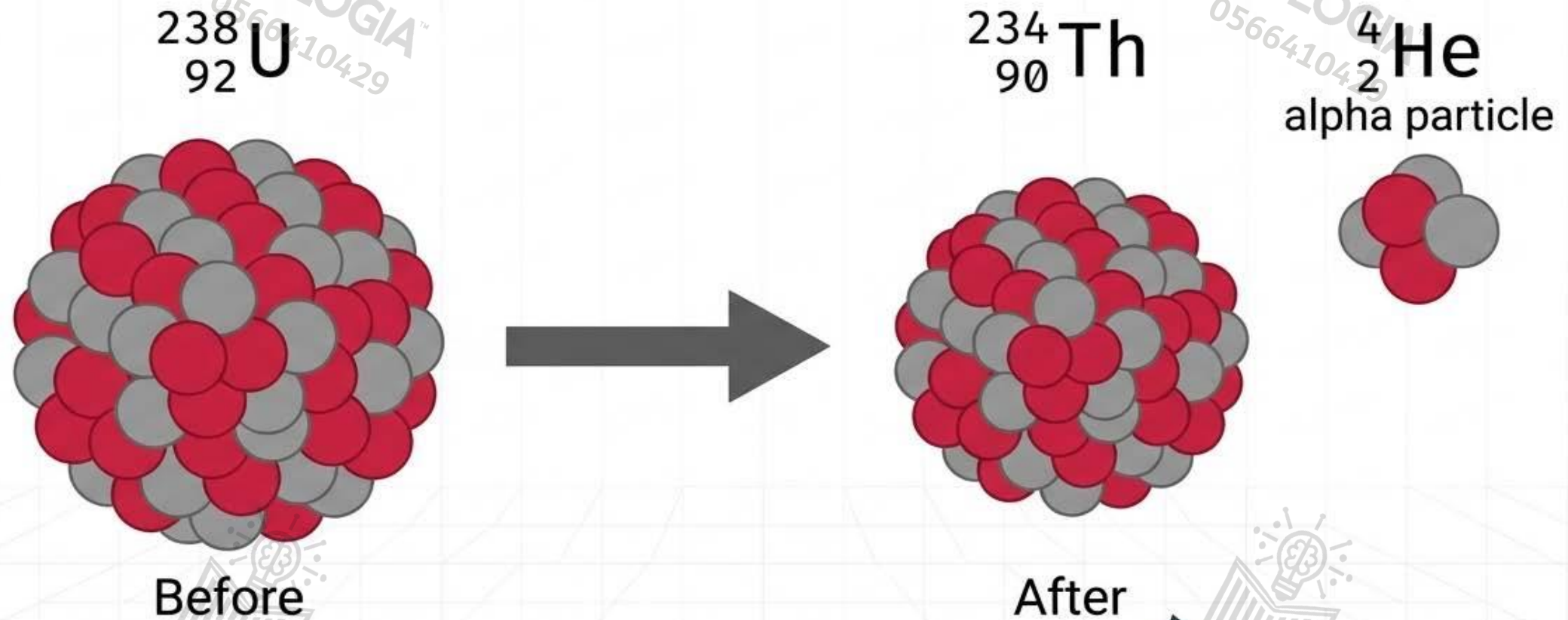
Mr. Mohamad's Tip:

Gamma rays often accompany alpha and beta decay. They redistribute energy to stabilize the nucleus but do not change the physical mass or elemental identity.

The Penetration Shield Diagram



Mechanics of Alpha Decay



Alpha decay occurs in massive nuclei (at least 106 nucleons).
The mass number drops by 4; the atomic number drops by 2.

Differentiating Beta Decay

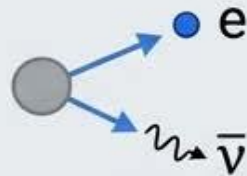
Beta Minus Decay β^-

Mechanism:

A neutron changes into a proton.

Emissions:

Ejects an electron and an antineutrino.



Result:

Nucleus gains a proton ($Z + 1$), but maintains its mass number (A).

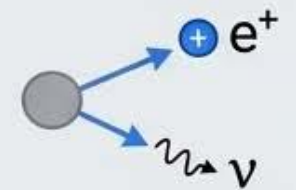
Beta Plus Decay β^+

Mechanism:

A proton changes into a neutron.

Emissions:

Ejects a positron (Charge $+1e$) and a neutrino.



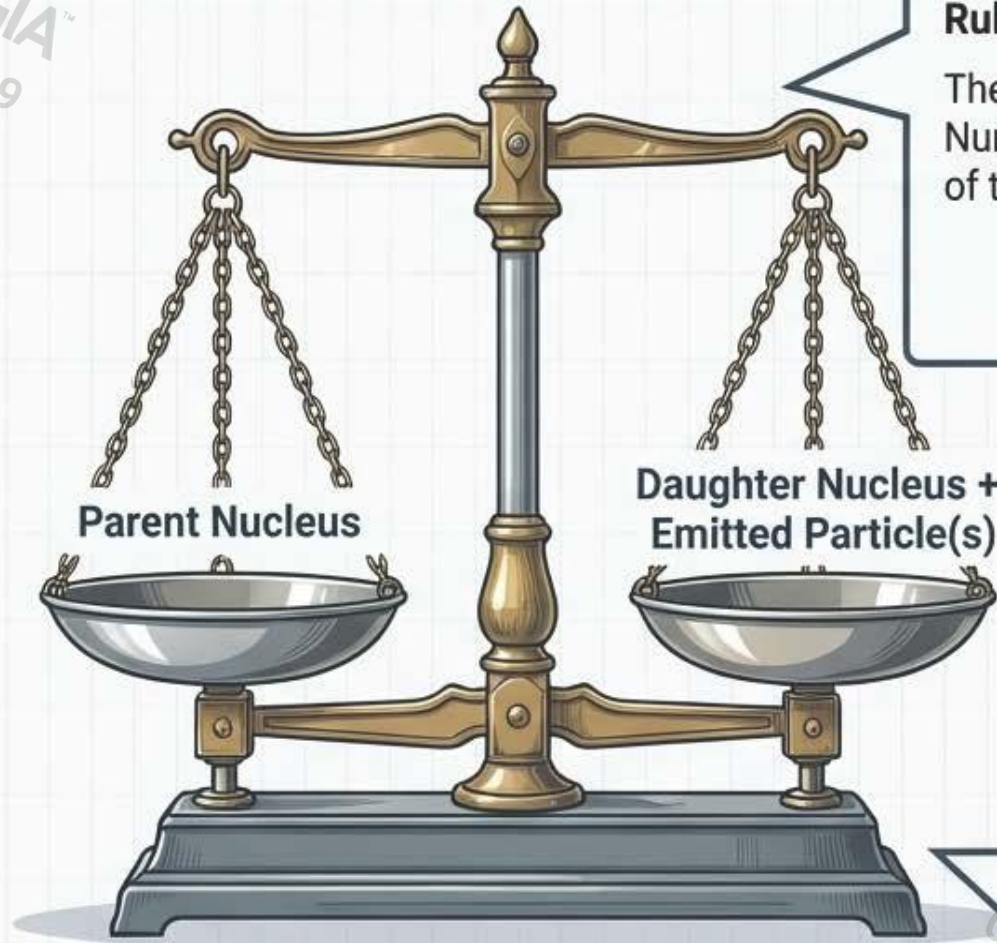
Result:

Nucleus loses a proton ($Z - 1$), but maintains its mass number (A).

Universal Rule of Charge Conservation

In ALL reactions, charge is perfectly conserved. The total charge before the decay exactly equals the total charge after.

The Mechanics of Balancing Nuclear Equations



Rule 1: Conservation of Nucleons (Mass)

The sum of the superscripts (Mass Number, A) on the left must equal the sum of the superscripts on the right.

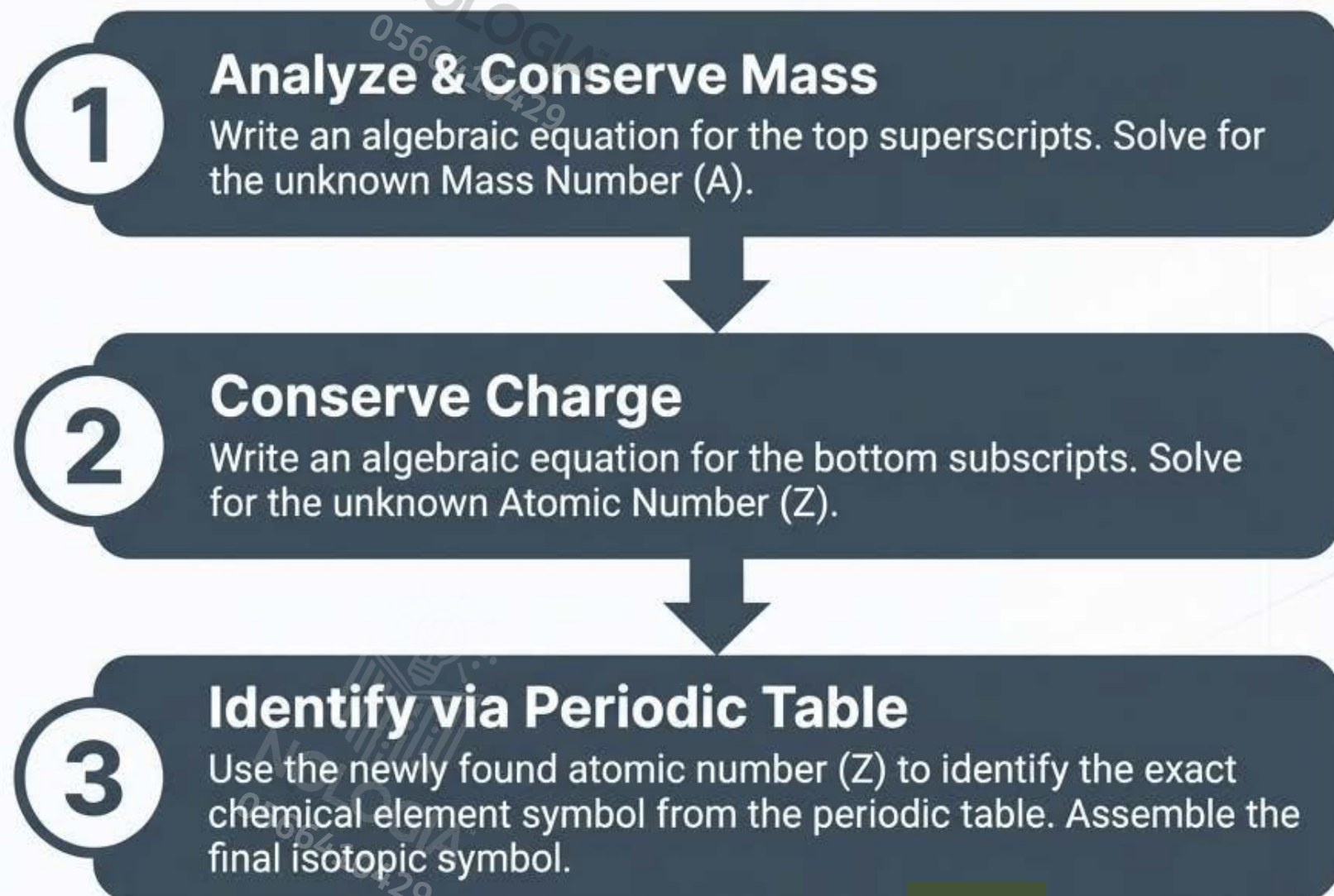
$$238 = 234 + 4$$

Rule 2: Conservation of Charge

The sum of the subscripts (Atomic Number, Z) on the left must equal the sum of the subscripts on the right.

$$92 = 90 + 2$$

Mr. Mohamad's 3-Step Diagnostic Flowchart



Mr. Mohamad's Tip:

Never guess the element based on the mass number! Always use Z (the subscript) to find the element on the periodic table. Protons exclusively dictate elemental identity.

Guided Example 1: Alpha Transmutation

Problem: Write the nuclear equation for radioactive radium isotope $^{226}_{88}\text{Ra}$ emitting an alpha particle to become the radon isotope $^{222}_{86}\text{Rn}$.

Step 1: Analyze Initial and Final States

Known

Initial: $^{226}_{88}\text{Ra}$.

Final: alpha particle (^4_2He) and $^{222}_{86}\text{Rn}$.

Step 2: Solve for Unknown



Step 3: Evaluate & Math Check

Mass Check: $226 = 4 + 222$
(Mass number is conserved) ✓

Charge Check: $88 = 2 + 86$
(Charge is conserved) ✓

Guided Example 2: Beta Transmutation

Problem: Write the nuclear equation for radioactive lead isotope $^{209}_{82}\text{Pb}$ decaying into bismuth $^{209}_{83}\text{Bi}$ by emitting a beta particle and an antineutrino.

Step 1: Analyze Initial and Final States

Known

Initial: $^{209}_{82}\text{Pb}$.

Final: $^{209}_{83}\text{Bi}$, **beta particle** ($^0_{-1}\text{e}$), and antineutrino ($\bar{\nu}$).

Step 2: Solve for Unknown



Step 3: Evaluate & Math Check

Mass Check:

$209 = 209 + 0 + 0$
(Mass number is conserved) ✓

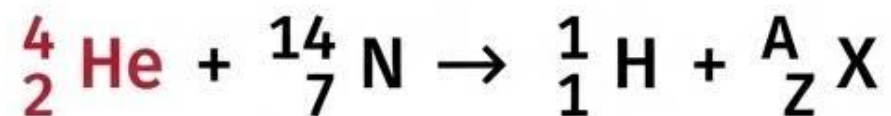
Charge Check:

$82 = 83 - 1 + 0$
(Charge is conserved) ✓

Guided Example 3: Particle Bombardment

Problem: Nitrogen gas ($^{14}_7\text{N}$) is bombarded with alpha particles (^4_2He), emitting a high-energy proton (^1_1H). What new isotope is created?

Step 1: Setup the Reaction



Step 2: Solve Algebraically for Unknowns

Solve for Z:

$$2 + 7 = 1 + Z$$

$$Z = 8$$

Solve for A:

$$4 + 14 = 1 + A$$

$$A = 17$$

Step 3: Identify & Finalize

Element with $Z = 8$ is oxygen.
The created isotope must be $^{17}_8\text{O}$.



The Temporal Decay Dashboard: Concept

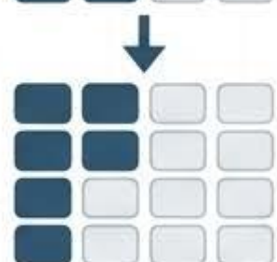
The Concept of Halving



$t = 0$ (100%)



$t = 1$ (50%)



$t = 2$ (25%)



$t = 3$ (12.5%)

Mathematical Definitions

Half-Life

The time required for half of the atoms in any given quantity of a radioactive isotope to decay.

Formula

Remaining = Original * $(1/2)^t$ (where t is number of half-lives)

Activity

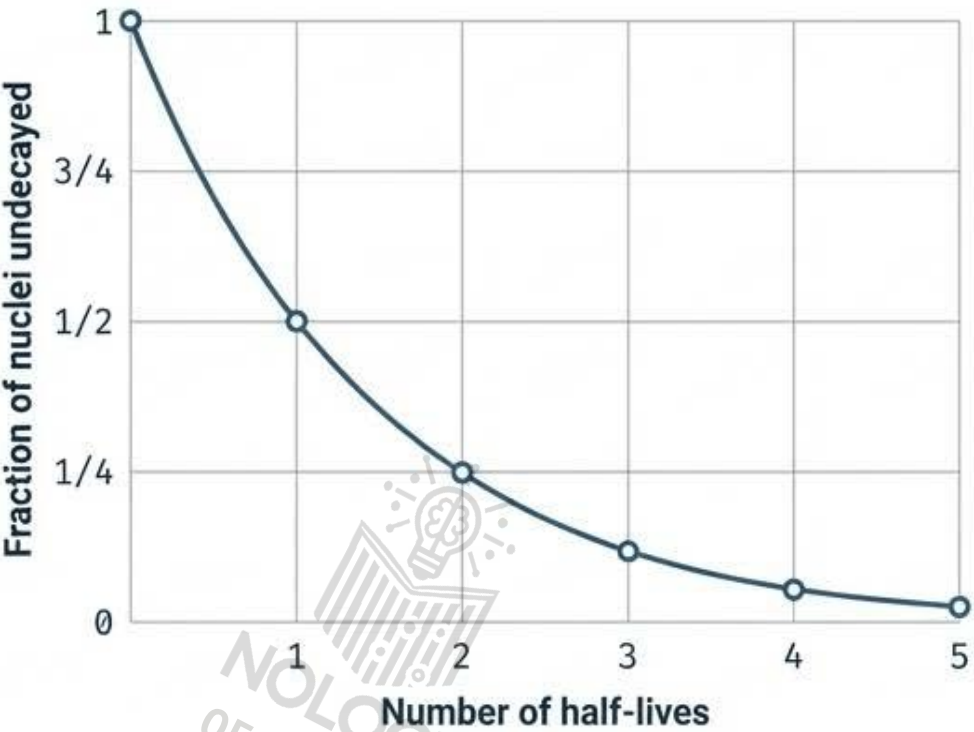
The number of decays per second of a radioactive substance. The SI unit is the Becquerel (Bq).

Mr. Mohamad's Tip:

Activity is strictly proportional to the number of radioactive atoms present. If you halve the atoms, you halve the activity.

The Temporal Decay Dashboard: Data

The Universal Curve



The Scale of Stability

Isotope	Half-Life Scale
Polonium-194 (194/84 Po) Fira Code	0.7 seconds (Micro-scale) Roboto
Iodine-131 (131/53 I) Fira Code	8.07 days (Human-scale) Roboto
Radium-226 (226/88 Ra) Fira Code	1,600 years (Historical-scale) Roboto
Uranium-238 (238/92 U) Fira Code	4.51 x 10^9 years (Geologic-scale) Roboto

Guided Example 4: Calculating Activity Over Time

Scenario: Iodine-131 has a half-life of 8.07 days. **Problem:** A sample of Iodine-131 has an initial activity of 8×10^5 decays/s. What is its activity after 8.07 days?

Step 1: Analyze Elapsed Time

Elapsed time is 8.07 days, which is exactly equal to one half-life ($t = 1$).

Step 2: Apply Formula

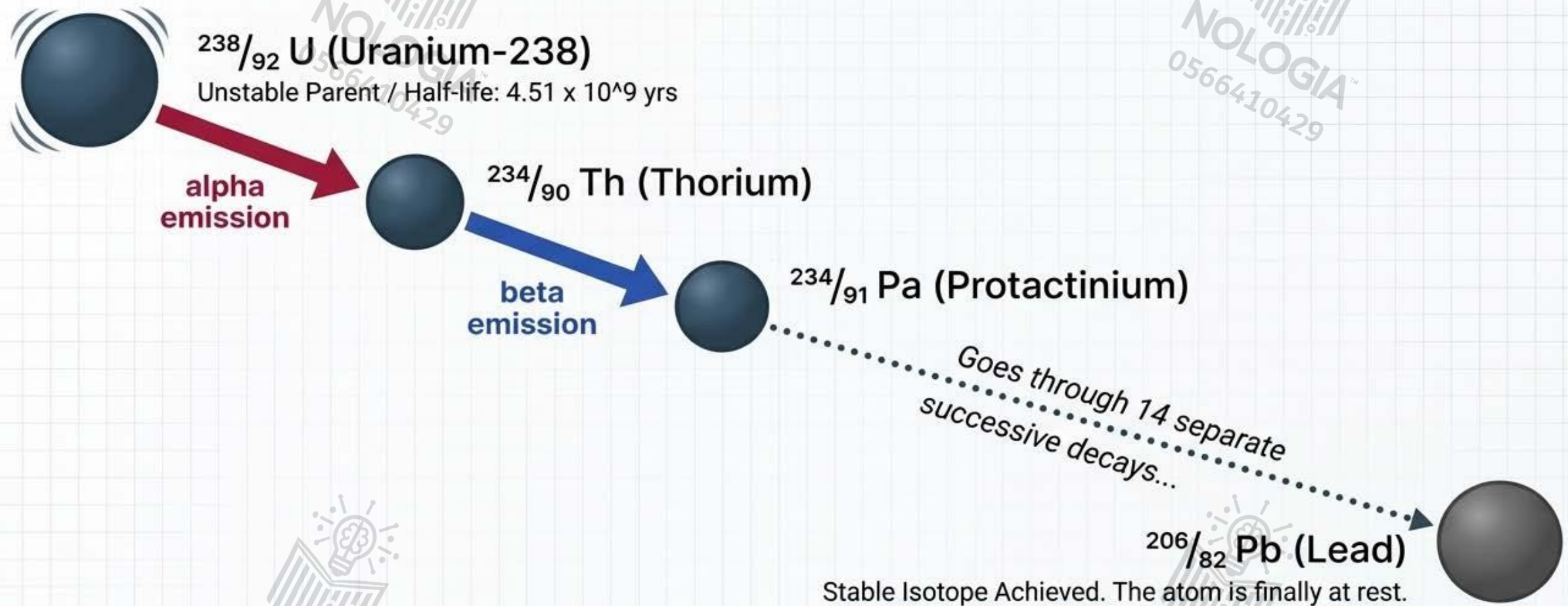
$$\begin{aligned}\text{New Activity} &= \text{Original Activity} * (1/2)^t \\ \text{New Activity} &= (8 \times 10^5) * (1/2)^1\end{aligned}$$

Step 3: Solve

$$= 4 \times 10^5 \text{ decays/s}$$

Follow-up Note: After another 8.07 days pass (making two total half-lives, $t=2$), the activity halves once again to 2×10^5 decays/s.

Synthesis: The Anatomy of a Decay Chain



Radioactive decay is not random destruction. It is a strictly governed mathematical journey toward ultimate physical stability.



1. Artificial Radioactivity

- Particle Bombardment
- Isotope Creation
- Medical Imaging



2. Nuclear Fission

- Splitting Heavy Atoms
- Exponential Chain Reactions
- Power Reactor Engineering

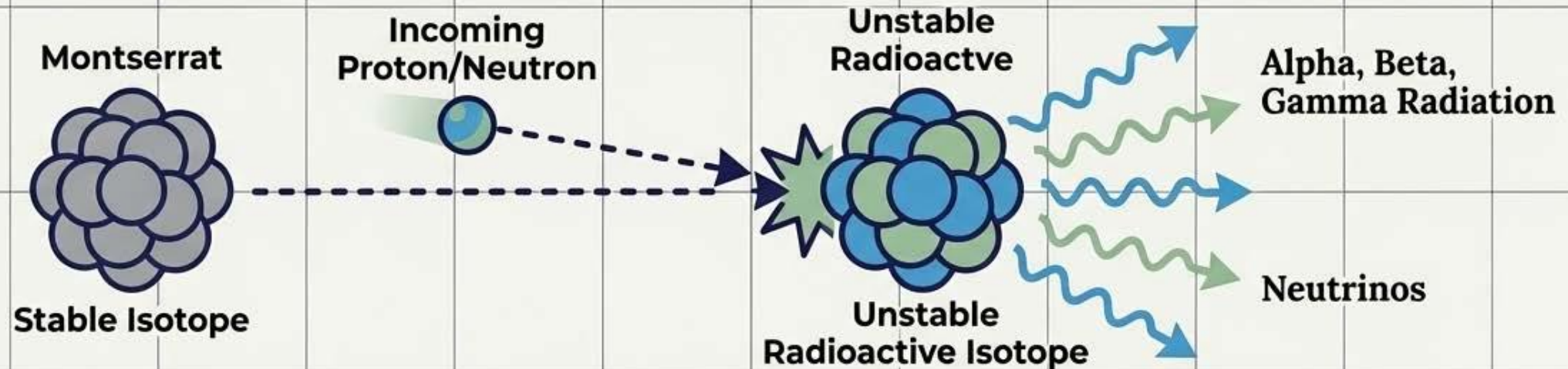


3. Nuclear Fusion

- Stellar Energy Production
- The Proton-Proton Chain
- Combining Light Nuclei

Creating Artificial Radioactivity

Core Concept: Radioactive isotopes can be artificially formed from stable isotopes by particle bombardment. These unstable nuclei emit radiation until converted back to stable isotopes.



The Positron ($+1^0e$): A positively charged particle with the exact mass of an electron.

Mr. Mohamad's Tip:

Remember: Artificially produced radioactive isotopes act as 'tracers' because external radiation counters can track their activity inside a system!

Application: Radiation in Medicine

Diagnostics (PET Scans)



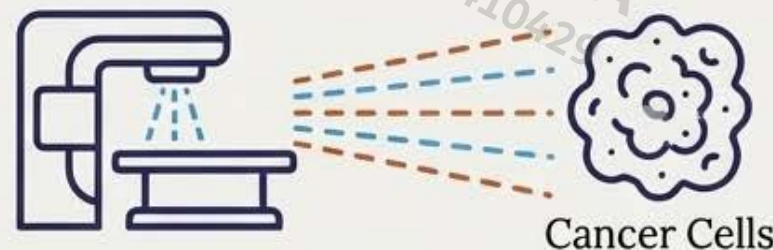
Process:

1. Radioactive solution is injected.
2. Isotope accumulates in target tissue.
3. Isotope decays and produces positrons.

The Reveal:

Positrons annihilate nearby electrons, producing gamma rays. The PET scanner detects these rays to map a 3D image.

Destruction (Cancer Therapy)



Rationale:

Cancer cells are highly sensitive to radiation because they divide more rapidly than normal cells.

Methods:

- **Method 1:** Gamma rays from Cobalt-60 target cellular structures.
- **Method 2:** Injected Iodine specifically targets thyroid cancer.
- **Method 3:** Particle accelerators beam particles directly into tissue.

Practice: Half-Life & Activity

Problem 25: Tritium Mass

Question: A 1.0-g sample of tritium is produced. After 24.6 years, what mass of tritium will remain? (Given: Tritium half-life is 12.3 years).

Step 1: Calculate Number of Half-Lives

$$24.6 \text{ years} / 12.3 \text{ years} = 2 \text{ half-lives.}$$

Step 2: Apply the Decay

$$1.0 \text{ g} \rightarrow 0.5 \text{ g} \rightarrow 0.25 \text{ g}$$

Solution: Mass remaining = 0.25 g.

Mr. Mohamad's Tip:

Always map the time elapsed to the exact number of half-lives before doing the math!

Problem 27: Polonium Activity

Question: A sample of Po-210 is purchased Sept 1. Activity is 2×10^6 Bq. What is the activity on June 1 (~274 days later)? (Given: Po-210 half-life is 138 days).

Step 1: Calculate Number of Half-Lives

$$274 \text{ days} / 138 \text{ days} \approx 2 \text{ half-lives.}$$

Step 2: Apply the Decay

$$\text{Activity halves twice: } 2 \times 10^6 \text{ Bq} \rightarrow 1 \times 10^6 \text{ Bq} \rightarrow 0.5 \times 10^6 \text{ Bq.}$$

Solution: Activity = 0.5×10^6 Bq.

Concept: Nuclear Fission (Splitting the Atom)



The Trigger:
1 Neutron

The Target:
Uranium-235

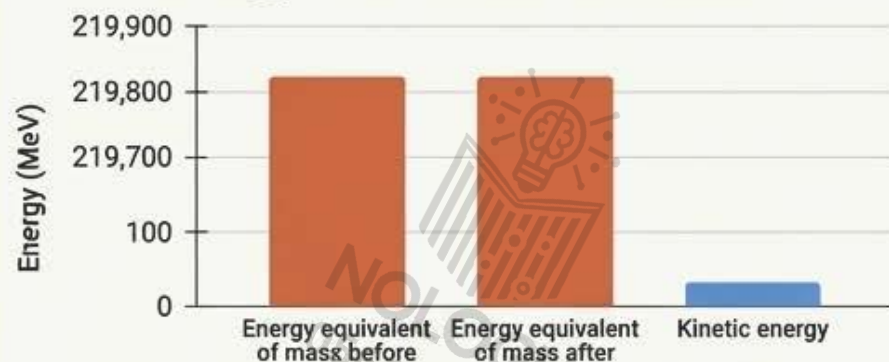
Equation Anatomy

The Fragments:
Barium & Krypton

The Multipliers:
3 Released Neutrons

The Output:
173 MeV Kinetic Energy

Energy in a Fission Reaction



In a fission reaction, the mass of the reactants is equal to the sum of the mass of the products and the mass equivalent of the kinetic energy of the products.

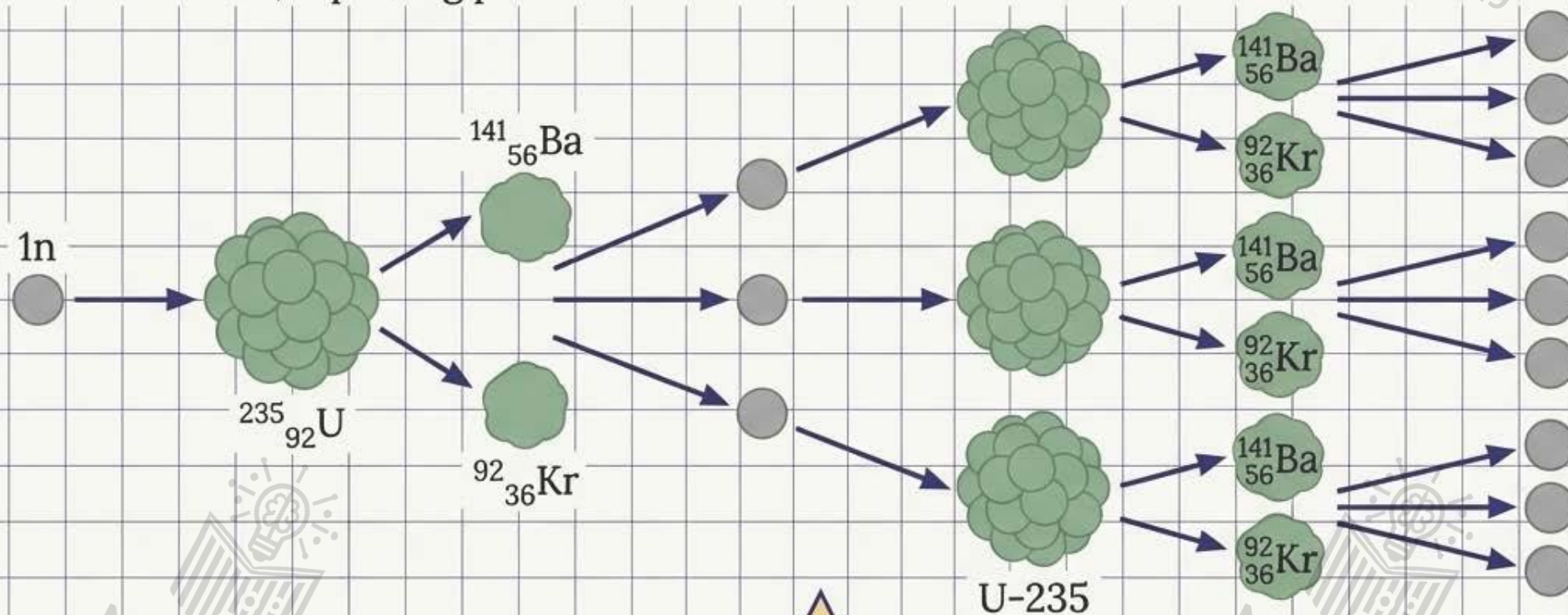
Mr. Mohamad's Tip

Mr. Mohamad's Note - Mass Defect:
Where does the 173 MeV come from? The mass on the right side is 0.186 u smaller than the left. That 'missing' mass is converted entirely into kinetic energy!

Mechanism: The Chain Reaction

The Chain Reaction

Each fission releases neutrons. These neutrons collide with additional $^{235}_{92}\text{U}$ nuclei, causing more fissions in a continuous, repeating process.

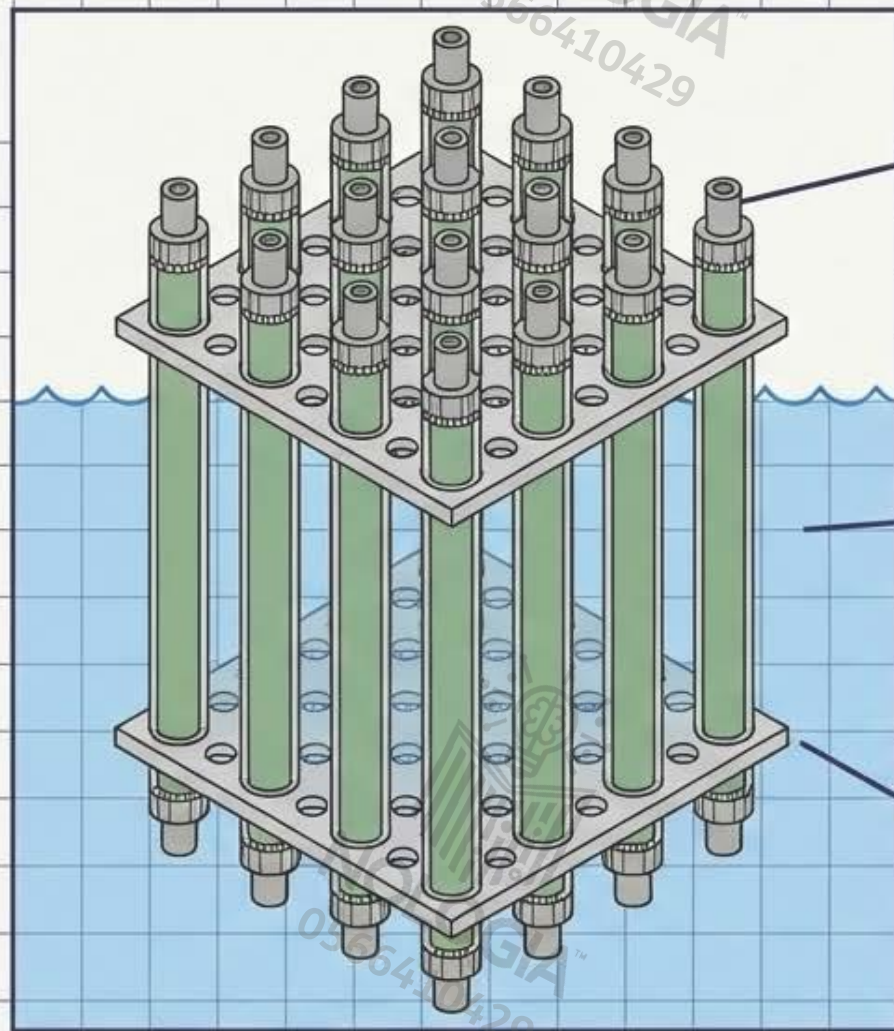


Mr. Mohamad's Tip:

Without control, this exponential growth is a bomb. With control, it's a **power plant**. The secret is those 3 released neutrons!

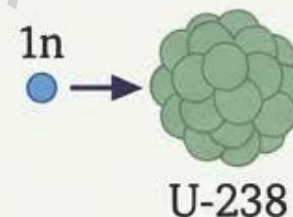
Application: Inside the Reactor Core

Controlling the Reaction



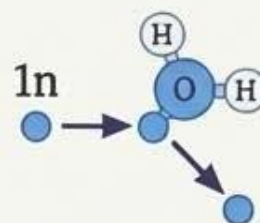
The Problem (Fast Neutrons)

Most neutrons released by fission are "fast" and are absorbed by $^{238}_{92}\text{U}$ without causing fission. We must slow them down to keep the chain reaction going.



The Moderator (Water)

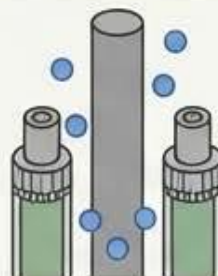
Light atoms in water collide with fast neutrons, transferring momentum and slowing them down so they are absorbed by the 1% of $^{235}_{92}\text{U}$. Water also absorbs **thermal energy**.



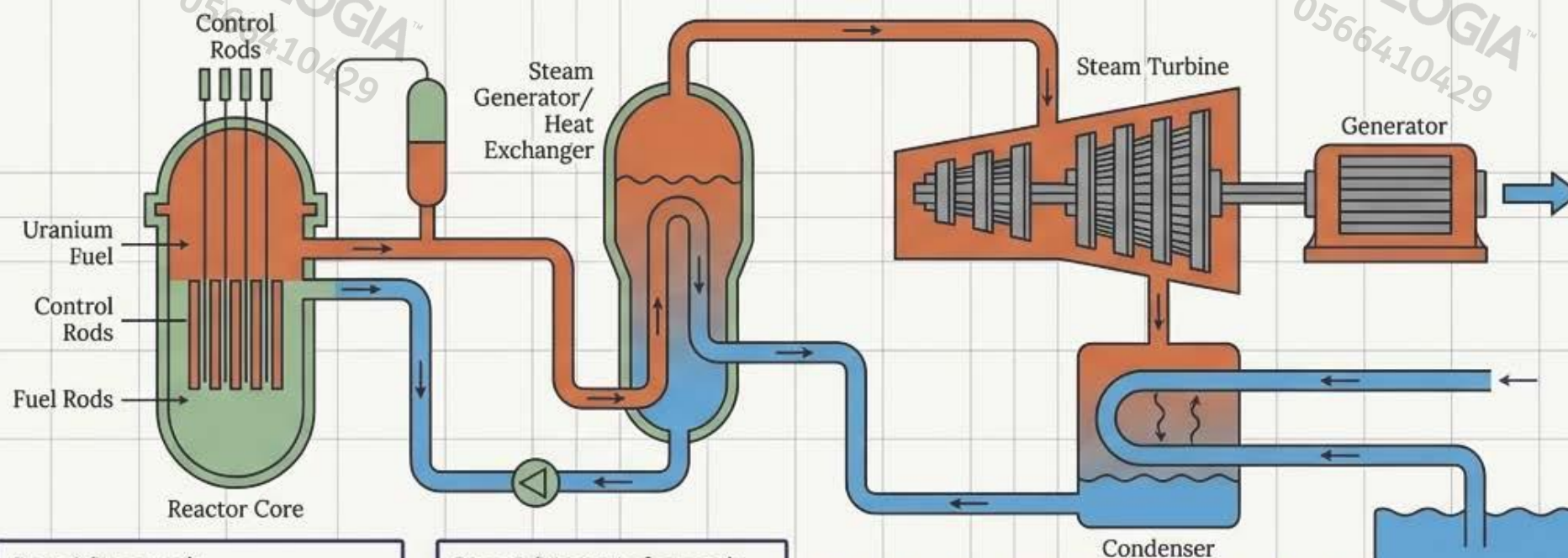
The Brakes (Cadmium Control Rods)

Cadmium easily absorbs neutrons.

- Insert rods = absorb neutrons = slow/stop reaction.
- Remove rods = free neutrons = increase energy release.



Application: From Atoms to Electricity



Step 1 (Reactor):
Energy released by fission heats pressurized water surrounding the uranium rods (does not boil due to high pressure).

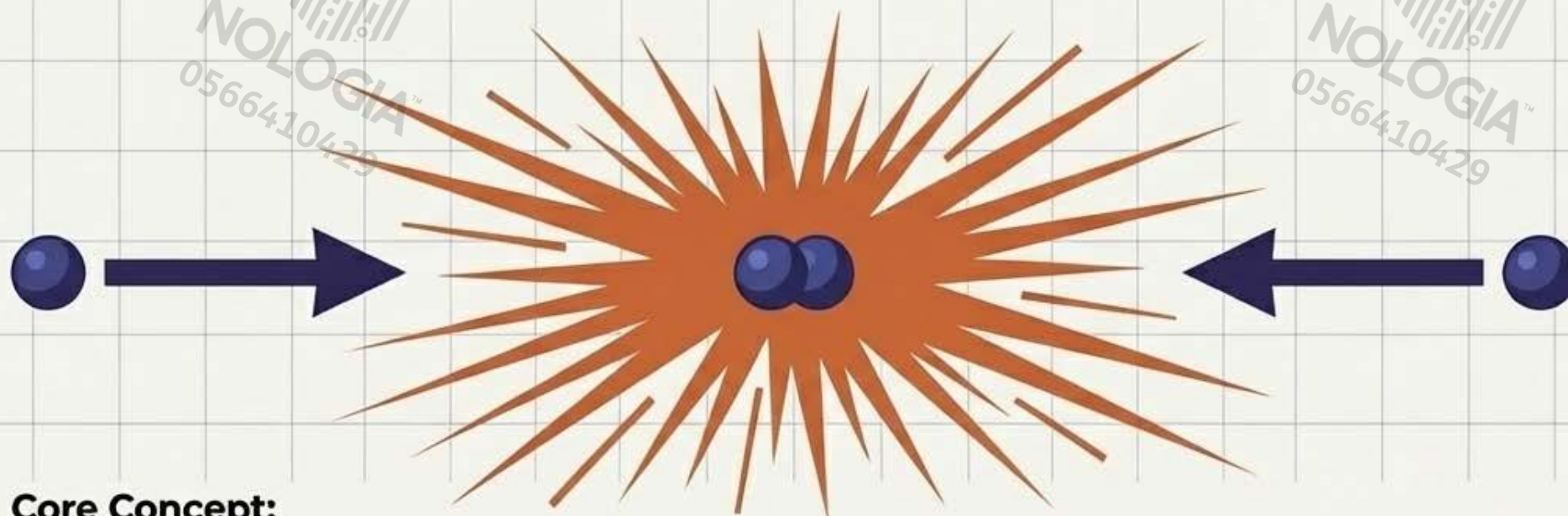
Step 2 (Heat Exchanger):
Extremely hot primary water is pumped to a heat exchanger, boiling secondary water into steam.

Step 3 (Turbine):
High-pressure steam turns the massive turbines.

Step 4 (Generator):
Turbines are connected to generators to produce electrical energy.

Mr. Mohamad's Note:
Most old fuel rod atoms (Krypton, Barium) remain highly radioactive. We currently store them securely as permanent disposal methods are being developed.

Concept: Nuclear Fusion (Combining Nuclei)



Core Concept:

Nuclei with small masses combine to form a nucleus with a larger mass.

The Energy Source:

The newly formed larger nucleus is more tightly bound. Its mass is less than the sum of the smaller nuclei. This distinct loss of mass corresponds to a massive release of energy.

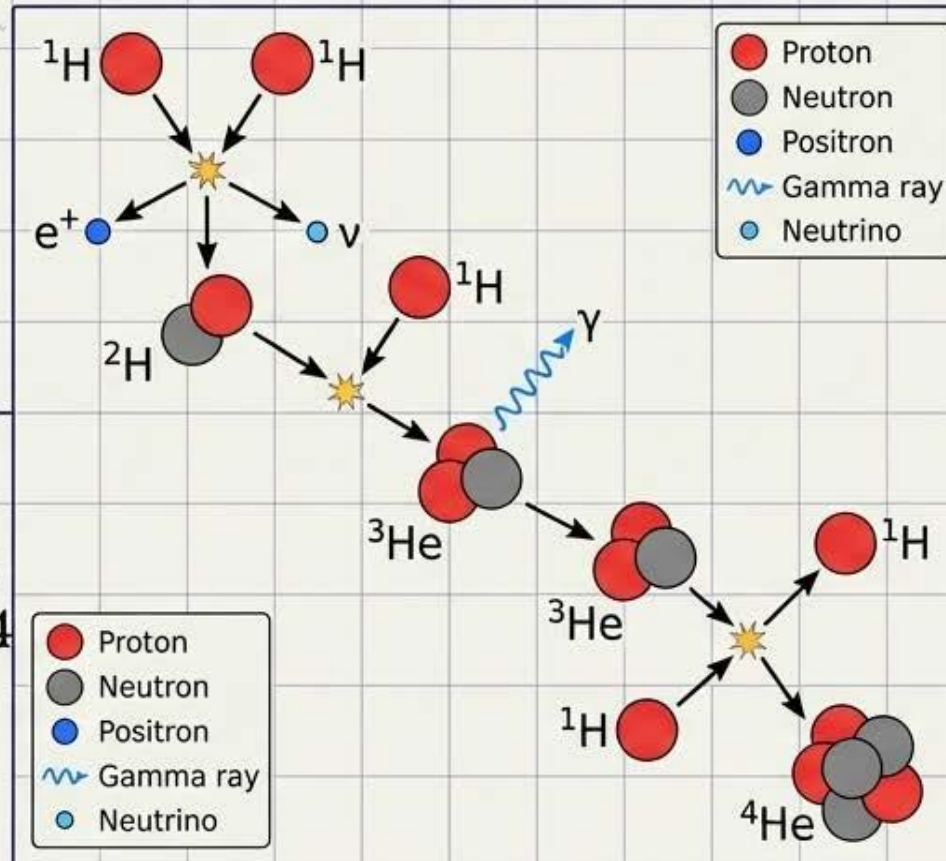
Mr. Mohamad's Tip:

Positively charged nuclei strongly repel each other. Fusion only happens when they have enormous thermal energy (around 2×10^7 K, like the center of the Sun) to overcome this repulsive electric force!

Mechanism: The Proton-Proton Chain

Step 1: Hydrogen nuclei (protons) fuse into Deuterium (^2H), releasing positrons and neutrinos.

Step 3: Two Helium-3 nuclei fuse to make stable Helium-4 (^4He), releasing two protons to continue the cycle.



Step 2: Deuterium fuses with more protons to make Helium-3 (^3He), releasing gamma rays.

Net Result: $4 \text{ Protons} \rightarrow 1 \text{ Helium-4} + 2 \text{ Positrons} + 2 \text{ Neutrinos} + 25 \text{ MeV}$

Synthesis: The Ultimate Comparison

Dimension	Nuclear Fission	Nuclear Fusion
Action	Splitting a heavy nucleus	Combining light nuclei
Fuel Example	Heavy elements (Uranium-235)	Light elements (Hydrogen/Protons)
Trigger	Neutron bombardment	Extreme heat/pressure ($\sim 2 \times 10^7$ K)
Byproducts	Radioactive waste (Barium/Krypton)	Clean, stable Helium
Energy Yield	~ 173 MeV per reaction	~ 25 MeV per reaction

Mr. Mohamad's Note: Wait, Fission releases more energy *per reaction* ($173 > 25$), but Fusion releases far more energy *per unit of mass* because hydrogen is so incredibly light!

Practice: Check Your Progress

Q: Beta Decay (Prob 29)

How can an electron be expelled from a nucleus during beta decay if the nucleus has no electrons?

Answer:

During beta decay, a neutron within the nucleus decays into a proton and an electron. The newly formed electron is then ejected from the nucleus.

Q: Nuclear Reactor (Prob 32)

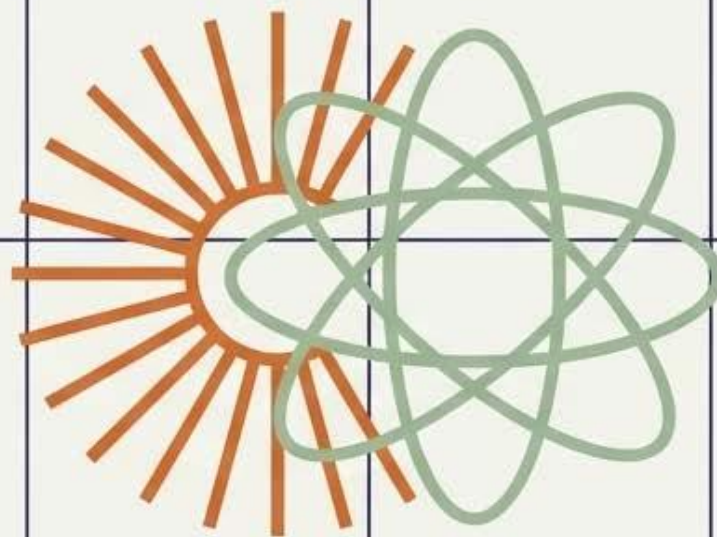
Lead is often used as a radiation shield. Why is it not a good choice for a moderator in a nuclear reactor?

Answer:

A moderator needs to slow down neutrons by absorbing their momentum. Colliding with massive, heavy atoms (like lead) causes neutrons to bounce off elastically with little energy loss. Light atoms (like hydrogen in water) absorb kinetic energy much more effectively during collisions.

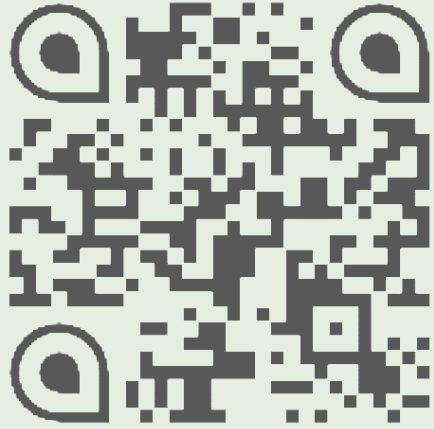
Mastery Achieved

You now understand the mechanisms that power our cities and the stars above. Physics is the blueprint of the universe—and you hold the key.



Review these frameworks, trust your understanding,
and best of luck in your exams!

— Mr. Mohamad



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